PARAMETRIC COST ESTIMATING AND RISK ANALYSIS OF TRANSPORTATION TUNNELING PROJECTS

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ABSTRACT

Due to the increased scrutiny of construction costs for infrastructure projects by the public and legislators, it is becoming increasing important for project developers to prepare accurate conceptual cost estimates for transportation tunnel projects at the feasibility stage to aid in making investment decisions. Past studies have emphasized that tunnel-project costs have been significantly underestimated, and cost uncertainties and risks have been identified as the cause of cost under or overestimation. A broad understanding of the factors that contribute to cost underestimation is important as it enables researchers and estimators to develop appropriate functions, evaluate, and implement them to produce realistic cost estimates.

This study was aimed at developing parametric cost estimation functions and quantifying their risks for transportation tunnel projects. A comprehensive background study of more than 39 published articles on transportation tunnel infrastructure projects was conducted through a systematic literature review and 40 key estimating parameters that may impact project costs and the associated project logistics were identified. Data from completed tunnel projects were collected and used to develop the parametric cost equations. Exploratory analyses were first performed to discover the correlations among tunnel costs and tunnel cost parameters/drivers. The purpose of this effort was to assess if a relationship existed between tunnel variables and tunnel project cost estimates. Parametric cost estimation functions were then developed for different tunnel applications. There has been no comprehensive study performed to date to develop parametric cost estimation functions that incorporated risk and uncertainty for transportation tunnel projects. Two representative sample case studies were performed and Monte Carlo simulation was used to quantify the associated risks. The results from the case studies illustrate the need to use appropriate techniques to simulate tunnel costs and quantify the risks associated with the estimates. The findings of the study provide a methodology to estimate the costs of transportation tunnels and quantify the uncertainties and risks associated with the costs. The methodology developed in this research could help reduce the incidence of project cost underestimation and alleviate some of the controversies surrounding cost overruns in transportation tunnel projects.

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DEDICATION

To the Almighty God, the provider of wisdom and knowledge.

I am grateful for His abundant mercies and blessings throughout this journey.

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CHAPTER 1. COST ESTIMATION AND UNCERTAINTY IN TRANSPORTATION TUNNEL PROJECTS

1.1. Introduction

Due to the increasing scrutiny of construction costs for infrastructure projects by the public and legislators, it is becoming increasingly important to prepare accurate conceptual cost estimates for transportation tunnel projects at the feasibility stage to aid in making decisions to build. Estimating transportation tunnel project costs is a highly complex and challenging process which involves uncertainties and risks such as limited available information as well as multiple unknown factors at the conceptual stage. Consequently, these risks and uncertainties if not considered in the cost-estimation process could result in cost under- or overestimation. This dissertation investigates factors that contribute to cost underestimation, analyzes and categorizes the factors identified, formulates hypotheses, develops novel parametric cost estimation function(s), and classifies the functions. In addition, models are developed and implemented to address the uncertainties and risks associated with transportation tunnel projects. This research further used the methodology proposed to conduct case studies on two transportation tunnel projects using the requisite function(s) developed. Overall, the research findings can be used by estimators, contractors, and consultants in North America, particularly USA, to prepare initial cost estimates for transportation tunnel projects and quantify the associated risks.

1.2. Problem Statement

Cost estimation for transportation tunnel projects at the conceptual stage is a complex and challenging process for estimators, contractor, and consultants because it involves uncertainties and risks. At this stage, accurate conceptual cost estimates are key in making sound decisions. In general, traditional cost-estimation methods such as unit price, cost per feet, or square feet are used to identify a project as a candidate for funding (Romero and Stolz, n. d.). Most of these applications rely on historical data not readily available in databases to calculate initial estimates for tunnel projects. It is also difficult to obtain comparable cost data across such projects, thus leading to cost underestimation and schedule problems for transportation tunnel projects (Rostami et al., 2013). The estimates for a proposed project are important because decision makers and the public rely on them to make multi-million or multi-billion dollar capital project decisions. Decisions based on deterministic assumptions will result in inaccurate cost estimates if risk and uncertainties are present. The Association for Advancement of Cost Engineering International (AACE) guidelines dictate that deterministic, stochastic, or a combination of the two cost estimation methods may be used depending on the level of project definition. Deterministic cost estimation methods are most applicable to projects with high level of definition while stochastic methods are appropriate at low levels of project definition.

Past studies, though, have shown that the use of traditional cost estimation methods to prepare tunnel-project costs are significantly underestimated (Merrow, 1988, Flyvbjerg et al., 2002, 2003a, 2003b, 2004, Flyvbjerg, 2009, Shane et al., 2009). Cost estimation is further compounded by multiple factors such as project complexity, undefined/unknown scope, uncertainties encountered, and the risky nature of underground construction conditions. It should be noted that parametric functions that are developed without considering risk/uncertainties do not show practical relevance. Therefore, it is essential to develop parametric function(s) that considers risk/uncertainty.

This research is motivated by the complexity and challenging process to produce accurate conceptual cost estimates due to the problems associated with uncertainties and risks, and multiple unknown factors at the feasibility stage especially for the transportation tunnel sector to minimize subjectivity of the theoretical models employed. This area has limited research hence the need for a better conceptual cost estimation function(s) and quantification of associated risks.

1.3. Research Objectives

The prime objectives of this study are to develop novel parametric cost function(s) and quantify associated risks to address the uncertainty and risks associated with transportation tunnel projects. The significance of this research are as follows:

1. Perform a systematic literature review to identify factors that contribute to cost underestimation in transportation tunnel projects in North America;
2. Analyze and categorize the identified factors based on their relative importance;
3. Collect data and develop cost estimation function(s) and classify them; and
4. Use the developed functions to perform cost estimation and quantification of associated risks for two tunnel project case studies.

1.4. Scope of Dissertation

The developed functions are applied to a wide range of transportation tunnel projects under different conditions. The rationale behind the correlation coefficients when performing simulations is beyond the scope of this study.

The basic concept of this research was to identify and evaluate factors contributing to cost underestimation in transportation tunnel projects in North America. Transportation tunnel project data and attributes are used to develop novel parametric cost estimation function(s) for transportation tunnel projects. In addition, risk analysis was performed using the parametric functions developed to quantify uncertainties and risks associated with tunnel transportation projects by conducting two case studies. The analyses and the development of cost estimation function(s) are based on data retrieved from a database administered by Dr. Jamal Rostami and

Mohmoud Sepehrmanesh of Pennsylvania State University and New Mexico Tech respectively, USA.

1.5. Significant Findings and Contributions

A comprehensive background study on more than 39 published articles on transportation projects involving tunneling review was conducted to elucidate key parameters that may impact project costs and associated logistics. To date, there has been no comprehensive study done for developing cost estimation functions that incorporate risk and uncertainty especially within the context of cost estimation functions beyond deterministic methods. Estimating the cost of transportation tunnel projects during the feasibility stage is highly complex and challenging for transportation personnel, estimators, consultants and contractors. To address this problem, forty key parameters were listed; they include engineering and construction complexities, geological/ground conditions, poor estimations, economic and market conditions, environmental requirements, scope changes, project size, technological innovation, political requirements, contract, and other possible underlying factors. A select list of these factors is further expounded, analyzed and evaluated using underlying probabilities. A ranking schema was developed to determine which estimating factors influence the cost estimate. The premise of this ranking was based on the number of times a factor occurred in the studies where those factors were discussed. The findings show the importance of incorporating the effect of estimating factors by transportation personnel to prepare accurate project estimates in avoidance of a cost underestimation.

This dissertation proposes the overall research paradigm, hypothesis, and procedure for developing a parametric cost estimation function for transportation tunnel projects. A novel schema diagram was designed for the development of the cost function by correlating the parameters to tunnel project costs. The functions developed were used to validate case studies, and to gain an insight on how tunnel costs fluctuate due to risks and uncertainties.

An exploratory data analysis (EDA) was conducted to gauge any underlying trend(s) or overarching elements that were required. This study also presents unique parameters used to develop cost estimate function(s) for tunnel projects. A sensitivity analysis was conducted to analyze the cost estimation function(s) developed with respect to input data to determine the risk. The proposed parametric functions provided realistic results, -60% to +110%, which compared well with Class 5 of AACE International range of values (-50% to +100%) at the screening or feasibility phase of a transportation tunnel project.

From this study, several cost functions were derived that can, within an agreeable limit of accuracy, predict costs associated with projects involving tunneling projects. These include: (a) for highway projects involving; (i) Drill and blast, (ii) Cut and cover and (iii) General cost function for all other scenarios, (b) Railway-based tunneling projects involving; (i) Tunnel Boring Machine (TBM), (ii) Mixed methods, and (iii) General cost function. This solution was a derivative of probability and statistics. The empirical functions for highway tunnel projects were calibrated using input data from background studies. The key parameters involved in deriving the cost functions were length of tunnel, diameter of tunnel and depth of overburden.

1.6. Dissertation Organization

This thesis is divided into seven chapters. This chapter begins with the introduction of the research by providing the background, problem statement, research objectives, scope of the dissertation, research significance and contribution, and lastly dissertation organization.

More specifically, following the introduction in Chapter 1, Chapter 2 describes a systematic literature review. This dissertation starts with a comprehensive literature review on factors that contribute tunnel project costs, estimation methods, theoretical models; and how current models address risk when calculating initial tunnel estimates. Basic descriptive statistics and Anderson-Darling statistical methods were employed to analyze the estimating factors and a discussion of the top-five factors that contribute to tunnel cost underestimation. The chapter goes on to present the limitations of the systematic literature review, conclusions, and future research.

Chapter 3 describes the cost estimation research paradigm. This chapter details research methodology, including hypotheses testing, data collection and pre-processing, and outlines the steps followed in the development of the function(s) to achieve the research objectives.

Chapter 4 deals with exploratory data analysis and curve fitting of the collected project data. Multivariable regression analyses and spread sheets were used in fitting functions. The functions for the quantification tunnel costs are classified. The functions selected for the different modes of transportation are used later in the thesis.

Chapter 5 discusses the development of parametric cost estimation functions for transportation tunnel projects on the basis of data analyses in Chapter 4. Chapter 4 presents the functions developed based on ground conditions in two ways; tunnel excavation methods and geology for the modes of transportation. The chapter concludes by demonstrating the use of the new functions developed by plotting the actual tunnel cost versus the estimated cost.

Chapter 6 describes uncertainty modeling and risk analysis of transportation tunnel projects. The @RISK is used in two applications to estimate costs and quantify the associated risks. The two case studies were conducted on the Port of Miami tunnel and the Seattle-Area Tunnel (SR 99).

Chapter 7 summaries the main achievement of the research work, presents the conclusions of the thesis, and provides areas for future research.

CHAPTER 2. ESTIMATING COST FOR TRANSPORTATION TUNNEL PROJECTS: A SYSTEMATIC LITERATURE REVIEW

2.1. Abstract

Estimating the cost of transportation tunnel projects during the feasibility stage is highly complex and challenging for state/federal agencies. The use of traditional methods to estimate tunnel project costs has led to significant cost underestimation because of limited information/data to compare different alternatives. To address cost underestimation, 40 cost estimating factors were identified by conducting a systematic literature review. Seven electronic databases were searched and articles were screened based on pre-established criteria. Of the 788 articles retrieved, 39 articles published from 1988 to 2013 met the inclusion criteria and were included in the review. The resulting data was analyzed using descriptive and Anderson-Darling statistical methods. The results of the analysis showed that the top-five factors contributing to cost underestimation were engineering and construction complexities, geological conditions, cost estimation, market conditions, and environmental requirements. The findings of this study showed the importance of incorporating the effect of each determined estimating factor by state/federal agencies or metropolitan planning organizations when preparing initial estimates to avoid cost underestimation and/or to reduce the errors associated with such estimates. Future research may be warranted to explore the possibility of weighting the parameters.

2.2. Introduction

Estimating the construction cost for tunnel projects is challenging and complicated because there are several unknown factors during the feasibility phase. Consequently, the cost estimation process becomes complex when considering these unknown factors. Proposed project estimates are important because decision makers and the public rely on them to make multi-million or multi-billion dollar investment decisions. Traditional cost estimation methodologies (unit price, cost per foot, or square foot) have been used to identify a project as a candidate for funding (Romero and Stolz, [date unknown]). However, these methods rely on historical cost data which are not readily available in databases to calculate initial estimates for tunnels projects. It is also difficult to obtain comparable cost data across such projects.

Transportation tunnels are used to provide passage through mountainous areas, across/under congested cities, or underwater. Tunnels might accommodate different transportation systems or utilities. The two types of transportation tunnels are rail and highway tunnels. Rail tunnels serve rapid-transit lines, commuter lines, or passenger/freight lines, while highway tunnels facilitate vehicular movement. Cities are becoming more congested due to high population densities with a corresponding demand for modern transportation and utility networks, resulting in a high demand for underground infrastructure (Duddeck, 1996; International Tunnelling Association [ITA] Working Group, 1988). As surface transportation infrastructure in urban areas continue to diminish, underground construction seems to be the only alternative.

Past studies show that state highway agencies and metropolitan planning organizations will require substantial investments for their endeavours to undertake such projects (Halabe, 1995). Furthermore, transportation tunnelling projects have often been plagued with cost underestimation, schedule growth, and high project contingency (Flyvbjerg et al., 2002, 2003b, 2004; Shane et al., 2009). In such cases, the consequences of inaccurate estimates could have far-reaching ramifications that might undermine public confidence in public organizations (Schexnayder et al. 2003, Flyvbjerg et al. 2009, and Chantarelli et al. 2010). Further, organizations might face litigation and be judged to have failed in their responsibilities of managing resources because cost estimates, schedule, and projected benefits are never met.

Since subsurface construction work is challenging, state highway agencies and metropolitan planning organizations might need to sponsor research aimed at addressing these challenges to help them achieve their mandate. Organizational strategies employed such as contingency sums to mitigate cost underestimation, have not been successful. The following are examples of transportation tunnel projects which have experienced substantial cost overruns even after appropriate strategies have been undertaken: the SR 99 Tunnel, the Holland Tunnel, and the Boston Central Artery/Tunnel at 49%, 300%, and 470% higher, respectively (Associated Press [AP], 2007; Shane et al., 2009; De Place, 2009) as shown in Table 2.1. Although several studies have been done to address cost underestimation of public projects (Flyvbjerg et al. 2002; 2003a; 2003b; and 2004, and Shane et al. 2009), it is still a significant problem.

Table 2.1. Examples of cost underestimations for transportation tunnel projects ($ in billions).

Project name	Year started	Year completed	Initial cost	Overall cost	Cost increase	Cost overrun (%)
Holland Tunnel	1920	1927	0.012	0.0484	0.0364	300
Central Artery/Tunnel (CA/T)	1993	2007	2.6	14.8	12.2	470
Seattle-Area Tunnel (SR 99)*	2011	Under construction	1.35	2.01	0.66	49

*The SR 99 project is only less 5% designed.

Tunnel projects are unique and large undertakings, making it difficult for small or large contractors to bid for such projects. For contactors to get such jobs, they generally form joint ventures. Transportation tunnelling projects are distinctive from other projects in the context that it is difficult to perform work from multiple locations due to its linearity where one operation has to be completed before the next one can start. It is further compounded by the risky nature of underground construction conditions. A systematic review of cost estimation factors does not exist. The primary objective of this study is to systematically select and review published literature and present an overview of the existing studies in identifying and analysing factors that contribute to cost estimation for transportation tunnelling projects. The study explored cost estimating factors, methods, models, and risk/uncertainty in conceptual estimates for transportation tunnel projects. The study used the following review questions: (1) what factors contribute to cost underestimation for transportation tunnel projects as entailed in existing literature? (2) What methods are used for the cost estimation of transportation tunnel projects? (3) What current models are used to estimate the cost for transportation tunnel projects? (4) How do current estimation approaches address the risks associated with tunnelling projects?

2.3. Previous Studies

Conceptual estimates can be defined differently depending on at what stage they are prepared during construction. In general, estimates are prepared at different stages of the construction process to allocate resources. Common definitions for initial estimates include "any estimate that has been prepared from inception of the project up to and including funding" (Oberlender and Frost, 2001), and "a compilation of all the costs of the elements of a project or effort included within an agreed upon scope" (Uppal, 1995). For tunnel projects, it is difficult to determine the final scope. In this case, estimates can be defined as approximate costs to perform construction work that are prepared until the time when a decision to build is made. The fundamental objective of an estimate is to aid in the decision making processes and create budgets.

Subsequently, it must be recognized that there is no standard cost estimation guideline to follow when developing a cost estimate for a tunnel project at the early stages. This is prompted by the amount of available information and the data used differ from project to project. Therefore, a cost estimation method may have to incorporate geotechnical conditions, excavation equipment, support requirements, environmental restrictions and policies, and money available to complete the tunnel project's estimate. Ideally, the extent of cost estimation (accuracy of the cost estimate) should be based on the specific project's requirements and complexity, rather than strict budget limits. However, for most transportation tunnels, especially tunnels in mountainous areas or for water crossings, costs for subsurface investigation might be prohibitive (Federal Highway Administration [FHWA], 2009). Therefore, the challenge to researchers is to develop a robust cost-estimation method that can improve the predictability of tunnel cost within a reasonable budget within an acceptable level of risk.

Constructing a transportation tunnel projects is a highly complex process and involves a variety of activities that are administered by different agencies and contractors. Tunnel works also encompass uncertainties and risks which increase with the project's complexity. Remington et al. (2009) defines a complex project as one that demonstrates a number of characteristics to a degree, or level of severity, that makes it extremely difficult to predict project outcomes, to control or manage the project. Complexity in projects is associated with uncertainty, difficulty, or organizational complicacy. De Meyer et al. (2002) and Williams (2005) concentrated on uncertainty, while Turner and Cochrane (1993); and Laufer, et al. (1996), Baccarini (1996), and Williams (2002) have focused on difficulty and organizational complicacy respectively. Risk is defined as, anything that influences the planning and execution of the project (Cabano, 2004), uncertainty of outcome, whether positive opportunity or negative threat of actions and events (HM Treasury, 2004), and an uncertain event or condition that can be positive or negative and that will have an effect on at least one project objective, such as duration, cost, scope, or quality

(The Project Management Institute [PMI], 2004). Risk is a combination of the probability of an uncertain event and its consequences that can be positive or negative. For transportation tunnel projects a wide range of factors contribute to tunnel complexity. Factors that contribute to the perception of complexity include difficulty, uniqueness, technology, unforeseen technical/financial challenges, change, and project management process among other factors. In the tunnel-construction processes, uncertainties could include geological conditions, support requirements, hydrogeological conditions, schedule, geomechanical, and cost risks that might negatively impact the project. Risk assessment needs to be factored into all stages of the construction process by looking forward and identifying potential problems; then, risk-mitigation strategies applied.

Ioannou (1988) presented a subsurface exploration and geologic classification based on available geologic information to select initial supports. The proposed method is difficult to implement due to the inherent limitations of site investigation in the feasibility phase. The contingency included in the initial estimate depends on the geologic data available and has been a point of disagreement since contractors believe that the method serves the design and does not serve construction. Flyvbjerg et al.'s (2002, 2003b) work on cost underestimation for infrastructure projects has been widely cited in the literature and by public officials. The researchers investigated 258 projects from different locations around the globe, covering forecasts and their economic viability and found that cost-estimation issues are not confined to a particular project or owner. The researchers highlighted the significance of cost underestimation and concluded that the problem is not limited to a particular geographical location, but spread throughout the world. Flyvbjerg et al. (2002, 2003a) concluded that estimating practices have not improved for the last 70 years, with 90% of projects resulting in cost underestimation. For tunnels and bridges, actual costs were, on average, 34% higher than estimated costs. The researchers' assumption is that cost underestimation is a historical problem and they do not consider any data from successfully completed transportation infrastructure.

Donnell (2005) and Shane et al. (2009) identified different factors that impacted the cost of highway projects, with Wu et al. (2005) studying 1,038 variation orders and found that design change is among the factors that contribute to cost underestimation. Chou (2009) developed a model for estimating the cost of transportation projects. While Reilly et al. (2011) presented an overview of the management for a complex underground tunnel project by proposing a methodology on how to improve the project delivery process.

In recent studies, Efron and Read (2012) examined 158 tunnel projects in 35 countries constructed at different years where they concluded that the final costs for transportation tunnel projects were higher than the initial costs. Their study explained the main issues that differentiate tunnels from other infrastructure projects. From their research, they also identified key cost drivers as the risk involved when undertaking excavation through unknown ground conditions and identified 16 factors in total that contribute to cost estimation of transportation tunnel projects.

2.4. Research Methodology

This study was performed as a systematic literature review (SLR) to search electronic databases to retrieve relevant literature (Falagas, and Karveli, 2006; Tang and Ng, 2006; Falagas et al., 2008) related to cost estimation for transportation tunnel projects. The SLR allows for an evidence-based approach to identify, select, analyse, and synthesize data for a specific research topic (Cook et al. 1997; Tranfield et al. 2003) by documenting all the steps. Denyer and Tranfield (2009) argue that SLR is different from other review methods because of its transparency, inclusivity, explanatory and heuristic nature to eliminate any bias and error issues which might arise. In the present work, the systematic review approach described by Rousseau et al. (2008) and Tranfield et al. (2003) was adopted to answer the systematic review questions formulated and establish the state of evidence with in-depth analysis and synthesis. A systematic review of this nature is important because researchers and practitioners depend on reviews to provide an up to date account and discussion of research findings in a particular area, to preview the methods that others have used, to reveal problems others might have experienced, and to identify sources of interest (Lipsey and Wilson, 2001).

2.4.1. Search, inclusion, and exclusion criteria

The following criteria are used for inclusion and exclusion of studies in the systematic literature review. Studies in English were considered from peer-reviewed journals (abstracts and full papers), conference papers, and theses published from 1988 to 2013. The papers included must have focused on transportation infrastructure and available to download. One book was included and considered at the same level as those of papers because it is an integral part of the current study. Studies not in English, not explicitly related to transportation infrastructure, or are not related to the review questions were excluded. Also excluded were prefaces, editorials, and poster sessions. Published research which had been peer reviewed was not independently assessed for study quality and was assumed to be of good quality and coded accordingly. However, research that was not published or was published without peer review was independently assessed by two reviewers for eligibility and quality and then treated the same as peer reviewed papers. The selection of both published and non-published research was aimed at performing a comprehensive search to help avoid the problem of upward bias which occurs when studies with only statistically significant results are likely to be published (Akobeng, 2005).

Based on the systematic review questions, a strategy was developed to identify relevant primary studies. The process involved a search strategy (identifying keywords and resources), data extraction strategy, and synthesis of the retrieved data. In some databases, no results were obtained when using Boolean searches or nesting; therefore, the structure of the search keywords were modified slightly to suit the individual search engines. First, keywords related to cost estimation for tunnel projects were extracted from the review questions. The list of search terms was constructed by noting key identifiers and descriptors from the review questions. The keywords included: 'cost estimating,' 'cost estimation,' 'cost underestimation,' 'risks,' and 'cost-estimation models.' Other keywords list was constructed from synonyms and included 'cost overrun in tunnels,' 'cost drivers in tunnels,' 'parametric cost estimation,' 'risk analysis in tunnels,' 'cost-estimation of tunnels,' 'cost escalation factors,' 'tunnels,' and 'cost growth.'

2.4.2. Databases searched

Second, resources to be searched about cost estimation were selected. The approach and databases searched are shown in Figure 2.1. The systematic review was performed by searching a combination of databases (such as the American Society of Civil Engineers [ASCE], Web of Science [WOS], Science Direct [SD], the Association for Advancement of Cost Engineering [AACE] International, and the Royal Institution of Chartered Surveyors [RICS]). Additional databases were the Transportation Research Board (TRB) and other web-based sources (i.e., Google). The search concentrated in databases rather than specific books or technical reports, as it was assumed that the major research results in books and reports are also described or referenced in journals. However, in cases where a book was identified to provide a comprehensive description relevant to the topic, it was included.

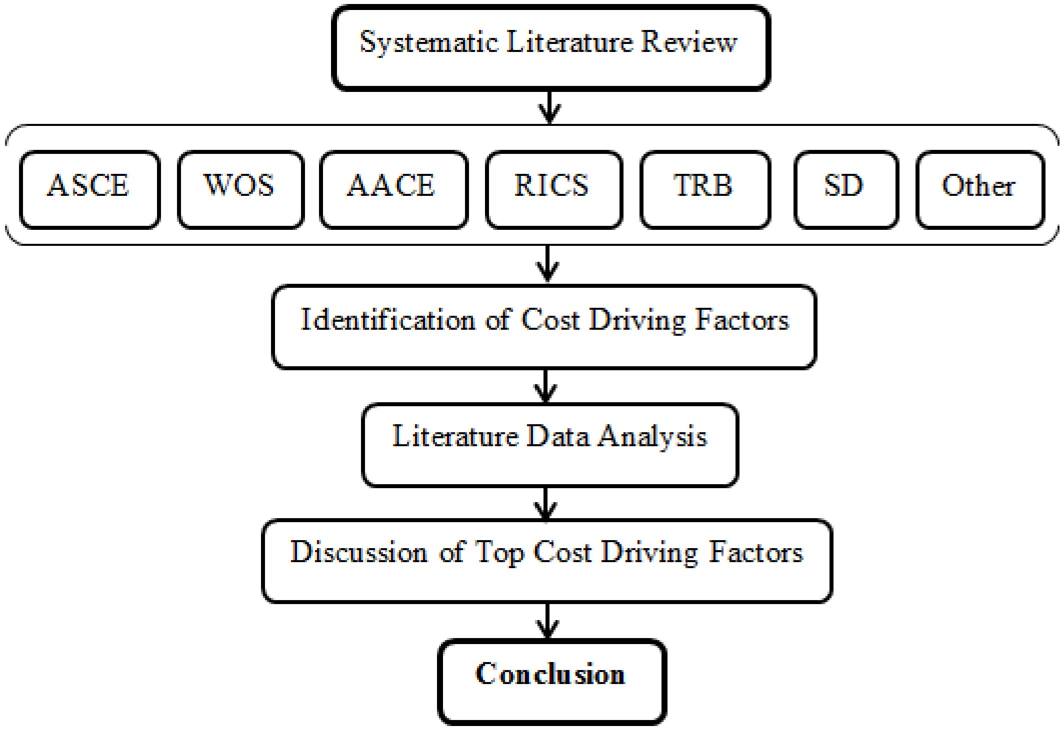

Figure 2.1. The steps followed

The databases were selected to ensure that a broad range of published and unpublished literature was retrieved on transportation tunnel projects. Some databases have open access search (e.g. Google), while others require prior subscription. The AACE database in the United States of America and RICS database in the United Kingdom were selected because they are each country's subject expert for cost engineering/estimation both with peer-reviewed journals and proceedings. The ASCE, WOS, and SD are major electronic databases about infrastructure projects and highly regarded by the academic community. The choice of the TRB was made because it covers topics about infrastructure projects and is highly recognized by the transportation community. The Google search engine was included to search cross-reference sources which might be difficult to find somewhere else. To identify all contributions, the same search sequence was adopted for all databases, but the words were modified slightly to suit the format of a particular database in order to avoid missing any new information.

To capture all the information, individual searches were performed directly on journals as well as for authors obtained from cross-referenced materials in the primary searches. The steps followed when conducting searches were: keywords search, identifying articles, and identifying articles cited by the author. The articles and documents were retrieved from different journals and government reports based on the criteria formulated. The procedure involved reading the abstracts, and in cases where the information was not available, the entire paper was read. The wide range of databases together with the use of predetermined terms searched was aimed at performing a broad review to generate a comprehensive list of articles.

After a document was obtained, estimating factors related to cost underestimation were examined to check its suitability for the review. The articles identified for review inclusion were assessed and then, the data extracted using a designed form. The data extraction form includes sections on search engines, factors, and rankings. The database headings were subdivided into author names and year the article was published.

Cost estimating factors contributing to cost underestimation for tunnel projects were identified and categorized into four groups: internal factors, external factors, project-specific factors, and other factors. Internal factors are defined as cost-growth factors that can lead to underestimation of costs during the planning and design phases of a typical project (Schexnayder et al., 2003). These factors can be controlled by the owner responsible for the project. Schexnayder et al. (2003) defines external factors as cost-growth factors for which the owner has little or no control regarding their impact on the project during the feasibility and design phases. In the results section, the frequency is the number of times each factor is identified in the different documents. The estimating factors identified were given the same weight, and the total score was the sum of the count data of the articles reviewed.

2.4.3. The selection of literature

The flow diagram of the systematic review (Figure 2) presents the number of papers identified at the various stages of the searches. From the searches, 788 articles were identified from searching seven databases, 92 abstracts and full text articles were assessed for eligibility, and 39 abstracts and full papers were considered in the analysis.

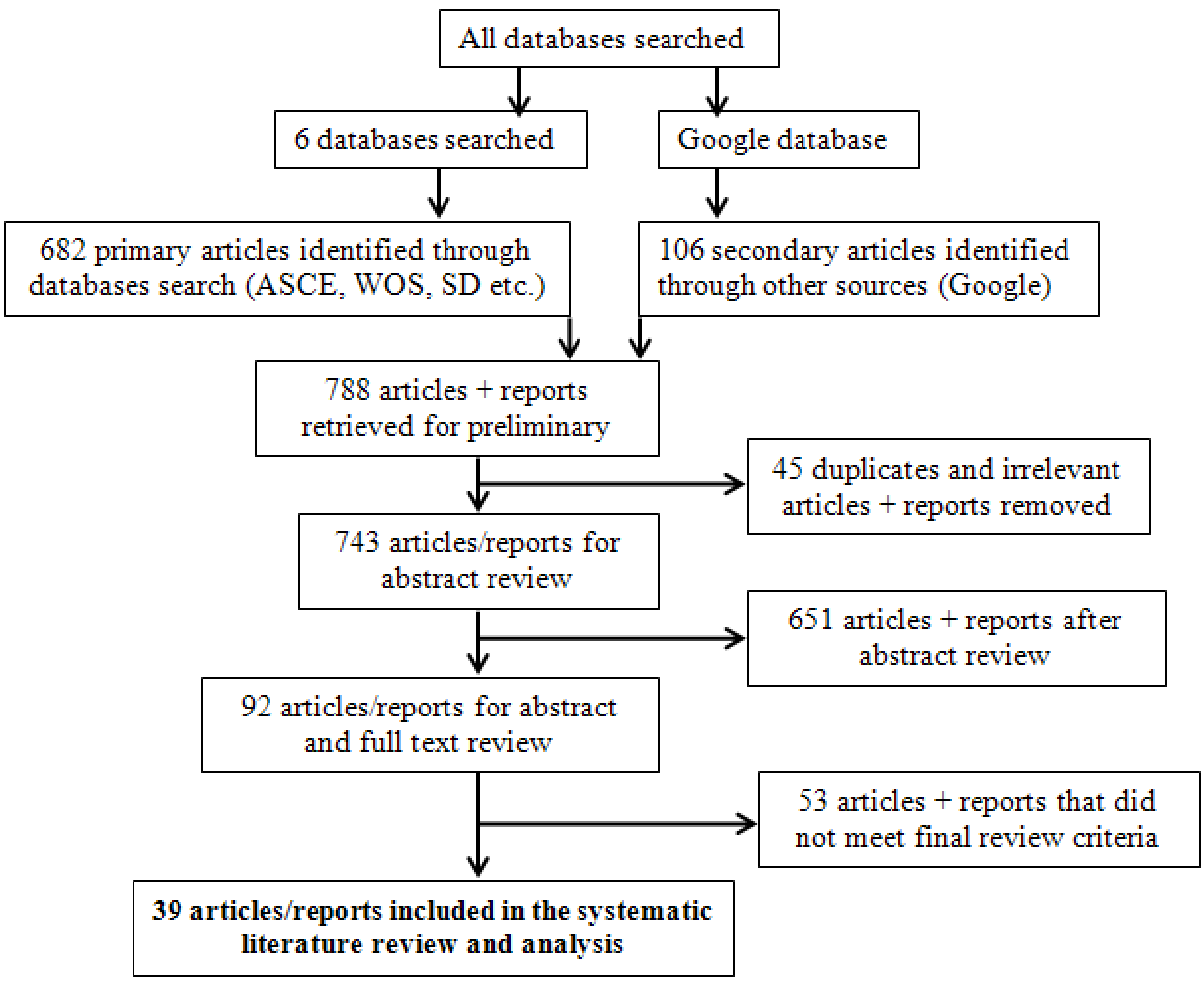

Figure 2.2. The search and selection process of the systematic literature review

A number of papers were not selected because the studies did not specifically discuss estimating factors contributing to cost underestimation of transportation infrastructure and the criteria for inclusion. The selected and analysed articles were from the 1988 to 2013 period. The tabulation of papers at the various stages from the seven databases is given in Table 2.2. The results show that other web-based search engines had 13 publications, the highest number, and closely followed by ASCE database with a total of 11 papers. The top two search engines were followed by SD and WOS with counts of 7 and 4 published papers, respectively. TRB and ACCE each had two articles. Searches made in RICS industry publications did not yield any results. The articles included in the review examined transportation tunnel projects. However, because of the few articles in this research field, papers from non-transportation tunneling projects have been included. The articles included covered transportation infrastructure projects.

Table 2.2. Papers reviewed at various stages.

Databases	Articles identified	Duplicates and not relevant articles	Articles after duplicate removal	Articles removed after abstract review	Articles for abstract and full text review	Articles which did not meet criteria	Articles included in the analysis
ACCE	120	0	120	118	2	0	2
RICS	60	0	60	60	0	0	0
ASCE	198	9	189	175	14	3	11
TRB	6	0	6	2	4	2	2
SD	278	19	259	216	43	36	7
WOS	20	0	20	15	5	1	4
Other	106	17	89	65	24	11	13

The papers and books were selected based on their discussion of estimating factors contributing to cost underestimation for transportation infrastructure. The final tally had 31 scientific journal articles and a dissertation. Also selected were three reports, one book, and three conference papers. Table 2.3 presents a sample of the literature and the factors they focused on. The articles considered were published in 12 peer reviewed journals and one book

Table 2.3. A sample overview of the literature.

Author(s)	Year	Journal/book title	Type of Study	Method/ Instrument	Sample size	Responders	Remarks/Assumptions
Akinci, B.; Fischer, M.	1998	Journal of Management Engineering	Explored uncontrollable risk factors using knowledge maps and cost overrun variables	Technical	-	-	The cost estimate of a project is affected by design and project-specific factors including; vagueness of scope, design complexity, and project size.
Akintoye, A.; Fitzgerald, M.	2000	Construction Management and Economics	Identified significant factors responsible for inaccurate estimates in the UK.	Survey/Q	84	Constructio n personnel	Insufficient time to prepare cost estimates, poor tender documentation, lack of understanding of project requirements, and estimators' lack of data processing skills affect project cost.
Akintoye, A.	2000	Construction Management and Economics	Identified several factors influencing cost estimating in the UK.	Survey/Q	84	Constructio n personnel	Project complexity, scope of construction, duration, market conditions, team requirements, and technology contribute to cot underestimation.
Anderson, S., Molenaar, K., Schexnayder, C.		Guidance for cost estimation and management for highway projects during planning, programming and preconstruction	Presents cost-estimation and management approaches to overcome cost escalation in all phases of development	Technical	-	-	Inadequate project scope, utility relocation requirements, right-of-way costs, environmental requirements, traffic-control requirements, and work-hour restrictions influence project cost.

Table 2.3. A sample overview of the literature (continued).

Author(s)	Year	Journal/book title	Type of Study	Method/ Instrument	Sample size	Responders	Remarks/Assumptions
Chan, S. L.; Park, M.	2005	Construction Management and Economics	Established a regression that depends on variables related to the characteristics of project determinants and construction team	Survey/Q	87	Architects, engineers, owners, and contractors	Three main groups of variables identified (i.e. characteristics of a project, contractors, and owner/consultants).
Chuo, J. S.	2009	Expert Systems with Applications	Proposed a generalized linear model for estimating cost for highways	Technical	-	-	The model considered project, location, right-of-way, designed speeds, and others.
Donnell, K. E.	2005	Thesis	Developed a preliminary list of strategies, methods, and tools for project cost estimation practices.	Survey/I	36	Public agency personnel	The preliminary list of factors causing cost escalation of highway project was grouped into internal and external factors.
Efron, N.; Read, M.	2012	Analysing International Tunnel Costs	Identified cost drivers and compared international tunneling costs.	Survey/ Q &I	-	Contractors, estimators, and consultants	Tunnel cost drivers including geology, excavation type, depth, length, lining type, market competition, and others.
Flyvbjerg, B.; Bruzelius, N.; Rothengatter, W.	2003a	Megaprojects and Risk: An Anatomy of Ambition	Provided several issues that result in cost underestimation.	Case study/ various methods	258	Construction industry personnel	Discussed issues such as technical mistakes, lack of experience, economic interests, and others.
Flyvbjerg, B.; Holm, M.K.S.; Buhl, S.L.	2004	Transport Reviews	Established that cost estimation is related to the length of the project implementation phase, the size of the project, and the type of ownership.	Survey/Q	258	Construction industry personnel	Project duration, size of project, and type of project ownership.

Table 2.3. A sample overview of the literature (continued).

Author(s)	Year	Journal/book title	Type of Study	Method/ Instrument	Sampl e size	Responders	Remarks/Assumptions
Haas, C.; Einstein, H	2002	Journal Construction Engineering and Management	Updated the Decision Aids for Tunneling (DAT) using observations from construction projects.	Technical	-	-	Geology and construction drives cost and does not take into account other factors.
Hoek, E.	2001	Journal of Geotechnical and Geoenvironment al Engineering	Presented a method for predicting squeezing conditions and how to deal with them.	Case study	2	-	Considers only geology and support systems.
Ioannou, P.	1988	Journal of Construction Engineering and Management	Explored geologic uncertainty and risk reduction in underground construction.	Survey/Q	-	Contractors	Assumes that geologic uncertainty and risk when well understood will decrease the cost of underground construction
Karam, K. S.; Karam, J. S.; Einstein, H. H.	2007 a	Journal of Construction Engineering and Management	Presented a virtual exploration approach before committing to actual work.	Technical /case study	-	-	Consists of geology, construction strategies, construction cost, and is only applicable in desk top studies.
Kimura, H.; Itoh, T.; Iwata, M.; Fujimoto, K.	2004	Tunneling and Underground Space Technology	Proposed a new mountain tunneling method consisting of an auxiliary and boring portion.	Technical /case study	1	-	Considers site conditions (geology, environment), design, and construction but only applicable for soft ground.
Molenaar, K.R.	2005	Journal of Construction Engineering and Management	Presented Washington State Department of Transportation's cost estimating validation process by considering programmatic risks.	Case study	9	Public personnel	Assumes that highway project have been historically been underestimated and identified programmatic risks responsible for the persistent problem.

Table 2.3. A sample overview of the literature (continued).

Author(s)	Year	Journal/book title	Type of Study	Method/ Instrument	Sample size	Responders	Remarks/Assumptions
Nutakor,G	2007	Cost Engineering	Conducted a qualitative and quantitative investigation on weights and impacts associated with final cost determining factors.	Case study/Q	14	Companies, consultants, and contractors	Low bid does not guarantee the final cost of a project since factors such as change orders, scope definition, bid process, contract risks, market conditions, risk management, and performance issues will affect the overall cost.
Paraskevopoulou, C.; Benardos, A.	2013	Tunneling and Underground Space Technology	Provides insight in cost estimation for underground projects.	Case based reasoning	9	Public	Geological and geotechnical conditions are the only factors influencing tunnel cost.
Petroutsatou, K.; Georgopoulos, E.; Lambropoulos	2012	Journal of Construction Engineering and Management,	Developed neural network model for an early stage cost estimation for road tunnels.	Survey/I	33	Designers, academics, and constructors	Geology, geological strength index, strain of the geological environment, and depth of overburden determines the initial cost.
Reilly, J. J.	2000	Tunneling and Underground Space Technology	Discussed an overview of management for complex, underground tunneling projects and suggested an improved methodology for the "project delivery process."	Technical	-	-	Environmental requirements, political requirements, legal requirements, team requirements, and others influence the initial tunnel cost.
Reilly, J. J.; Laird, L.; Sangrey, D.; Gabel, M.	2011	ITA World tunnel Congress, Helsinki	Presented the use of probabilistic cost estimating in the management of complex projects.	Case study	-	-	Provides a better understanding and communication of the risks involved in all phases of the construction process.

Table 2.3. A sample overview of the literature (continued).

Author(s)	Year	Journal/book title	Type of Study	Method/ Instrument	Sample size	Responders	Remarks/Assumptions
Rusteika, S. F.; Boomer, J. L.	1992	Association of Advancement of Cost Engineering [AACE] International Transactions	Developed a contingency assessment as a percentage of the estimated construction cost similar to different percentages for different cost items.	Case study	-	-	Design difficulty, geological conditions, economic environment, joint occupancy, schedule constraints, period of performance, urban environment, and others affect the conceptual estimates.
Schexnayder, C.J.; Weber, S. L.; Fiori, C.	2003	Transportation Research Board	Prepared a strategic approach for cost estimating issues in their synthesis on preparing and declaring early cost estimates.	Survey/Q & I	50	Public sector agencies	Project scope changes, engineering and construction complexities, changes in economic and market changes, effects of inflation, and others as affecting early estimates.
Shane, J. S.; Molenaar, K. R.; Anderson, S.; Schexnayder, C.	2009	Journal of Management Engineering	Categorized 18 primary factors which impact the cost of all construction projects.	Literature review/I	20	Public sector agencies	Delivery/procurement approach, engineering and construction complexities, scope changes, faulty execution are among escalation factors identified.

Note: Q stands for questionnaire, and I is interview

The journals included *Journal of Management Engineering*, *Construction Management and Economics*, Transportation Research Board, *Journal of Construction Engineering and Management*, and *Tunnelling and Underground Space Technology*. With most of the articles published in the *Journal of Construction Engineering and Management*, and it was followed by *Tunnelling and Underground Space Technology*.

Figure 2.3 summarizes some of the articles which have shaped the debate on estimating the cost of transportation infrastructure projects leading to cost underestimation and illustrates the timelines. The figure also includes authors who have conducted significant studies about identifying estimating factors that contribute to cost underestimation. The tunnel projects are included in this timeline to highlight the problem of cost underestimation; which is the focus of the present work. The timeline also covers two transportation tunnel projects due to their extensive media coverage. The criterion for selecting the two tunnel projects is their exposure in both electronic and print media. The CA/T project has the highest cost overrun and the SR 99 Tunnel still under construction with a substantial percentage already (AP, 2007; De Place, 2009).

There has been considerable research conducted over the past twenty four years focused on estimating factors that have contributed to cost underestimation for tunnel projects. The distribution of the reviewed papers by publication year shows that there were 2 papers from 1988-1993 and 3 from 1994-1999, peaking at 18 from 2000-2005. In the period 2006-2011, the number of articles declined to 13, further decreasing to 2 at the start of the 2012-2017 period. The majority of these studies on cost underestimation were performed in the last 10 years after Flyvbjerg et al.'s ground-breaking work on planning and implementing large infrastructure projects (2002, 2003a). Examples of major projects that have experienced considerable cost underestimation included the Boston's Central Artery/Tunnel project, the Washington's Alaskan

Way Viaduct project, and the Channel Tunnel; all of them were highly discussed by the media (AP, 2007; De Place, 2009).

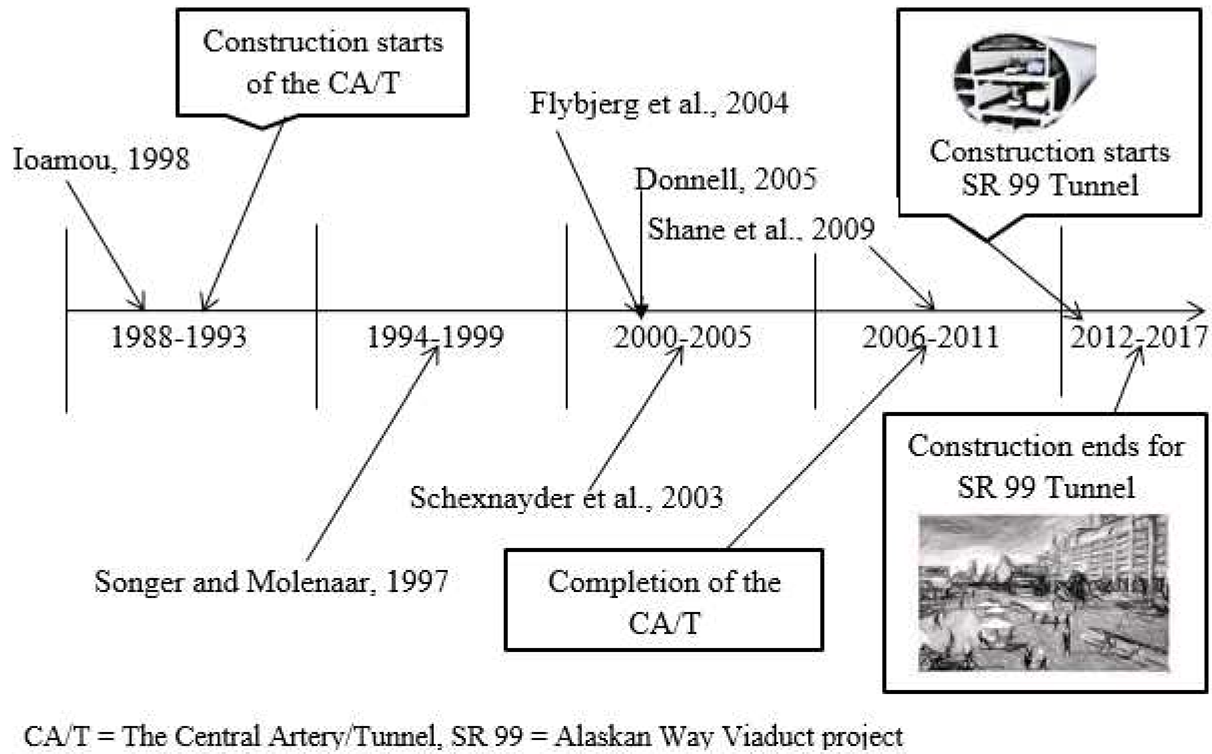

Figure 2.3. Literature review and project timelines

2.5. Results

A summary of the results of the review questions is presented.

2.5.1. Estimating factors contributing to cost underestimation

Review question 1 is related to identifying estimating factors that contribute to cost underestimation for tunneling projects. After conducting the search, a total of 40 estimating factors, published in 39 journals, were identified as contributing to cost under-estimation for infrastructure projects. The factors were categorized into four major groups: internal factors, external factors, project-specific factors, and other factors. Table 2.4 presents the breakdown, frequency, and rank for the 40 identified factors that contribute to cost underestimation for tunnel projects. The significance of a factor was weighed by the number of times the factor occurred in the literature.

The count data for estimating factors (Table 2.4) contributing to the cost underestimation for tunnel projects are the number of times a factor occurs in the literature. A total of 40 estimating factors were identified, and ranks were assigned to the counts. The factors with the largest integer are ranked 1, the second highest as 2, and others. A total of three factors received just one author's opinion, which was ranked as the lowest rank of 14. The percentage distributions for the four major group factors were project-specific, 36%; internal, 29%; others, 21%; and external, 14%, as the level of influence as shown in Figure 2.4.

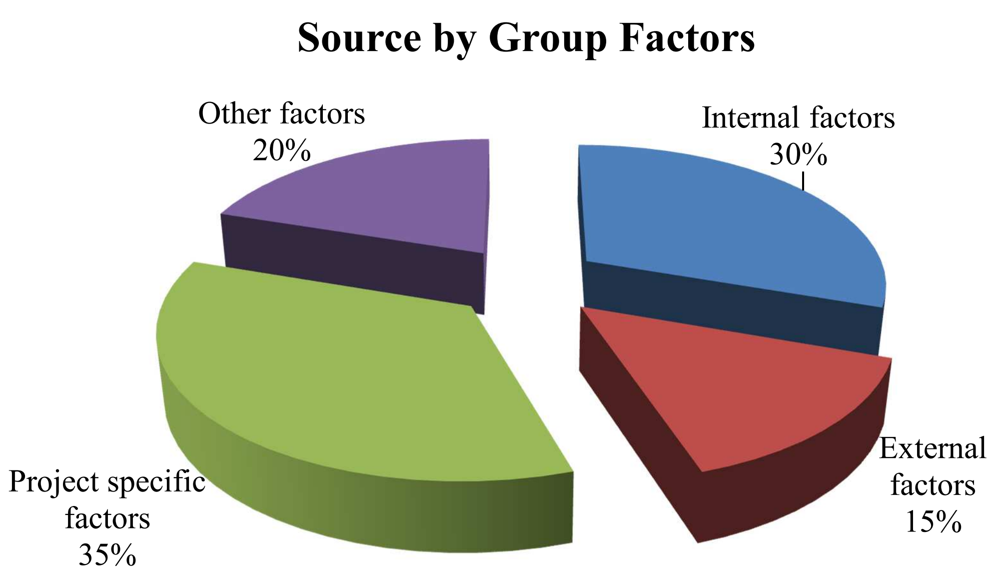

Figure 2.4. Percentage on the basis of source group factors

Table 2.4. Estimating factors contributing to cost underestimation for tunnel projects.

Search Engine		ASCE											Web of Science				TRB		AACE	
Authors		Ioannou, P.	Songer & Molenaar	Akinci & Fischer	Hoek, E.	Haas & Einstein	Trost and Oberlender	Karam et al.	Karam et al.	Shao & Macari	Surahyo & El-Diraby	Petroutsatou et al.	Flyvbjerg et al.	Flyvbjerg et al.	Shane, J. S. et al.	Petroutsatou et al.	Schexnayder et al.	Anderson et al.	Rusteika and Boomer	Nutakor,G
Year		88	97	98	01	02	03	07a	07b	08	09	12	03	04	09	12	03	07	92	07
Internal Factors	Bias			x											x					
	Delivery/procurement approach														x					
	Project schedule changes														x				x	x
	Engineering and construction complexities	x	x	x		x		x							x		x	x	x	x
	Scope changes														x		x	x		x
	Scope creep														x					
	Poor estimating (cost estimation)	x			x		x				x	x	x		x	x	x			x
	Inconsistent application of contingencies	x													x					
	Faulty execution														x					
	Ambiguous contract provisions														x					x
	Contract document conflicts		x	x											x					x
External Factors	Local government concerns and requirements														x					
	Effects of inflation														x		x			
	Project scope		x	x											x		x			
	Scope creep														x					
	Economic and market conditions	x	x	x											x		x		x	x
	Unforeseen events	x													x					
	Unforeseen conditions	x													x					

Table 2.4. Estimating factors contributing to cost underestimation for tunnel projects (continued).

	Factors	ASCE											Web of Science				TRB		AACE	
Project Specific Factors	Nature/type and length of project implementation													x			x		x	
	Size of project	x	x	x										x			x			
	Geological/ground conditions	x		x	x	x		x	x			x				x			x	
	Support measures	x			x					x	x									
	Environmental requirements						x				x						x	x	x	
	Site investigation	x																		
	Excavation method	x				x														
	Safety	x															x			
	Changes on project specs and design							x												
	Tunnel diameter											x								
	Tunnel length							x	x											
	Depth of overburden											x								
Other Factors	Type of project ownership		x											x						
	Geographical location							x					x							x
	Water problems	x			x															
	Social issues																			
	Technological innovation		x				x										x			
	Government standards and regulations		x				x										x			
	Political requirements			x													x			
	Local governmental pressures																x			
	Lack of organizational capacity		x														x			
	Inexperienced personnel																x			

Table 2.4. Estimating factors contributing to cost underestimation for tunnel projects (continued).

Search Engine		Science Direct							Other														
Authors		Einstein, H.H.	Reilly, J. J.	Kimura et al.	You et al.	Chuo J-S	Wu et al.	Paraskevopoulou and Benardos	Akintoye, A	Akintoye and Fitzgerald	Flyvbjerg et al.	Flyvbjerg et al.	Chan & Park	Donnell, K. E.	Molenaar, K.R.	Wagner, D.	Gil et al.	Flyvbjerg, B.	Cantarelli et al.	Reilly et al.	Efron and Read	Total	Rank
Year		96	00	04	04	09	05	13	00	00	02	03	05	05	05	06	06	09	10	11	12		
Internal Factors	Bias													x				x	x			5	10
	Delivery/procurement approach													x								2	13
	Project schedule changes													x								4	11
	Engineering and construction complexities	x		x		x	x		x				x	x	x					x		19	1
	Scope changes					x	x							x					x	x		9	6
	Scope creep																					1	14
	Poor estimating (cost estimation)									x	x	x		x				x		x		16	3
	Inconsistent application of contingencies													x								3	12
	Faulty execution																					1	14
	Ambiguous contract provisions		x																			3	12
	Contract document conflicts								x				x						x			7	8
External Factors	Local government requirements													x								2	13
	Effects of inflation											x		x								4	11
	Project scope									x			x									6	9
	Scope creep													x								2	13
	Economic and market conditions					x			x					x	x			x	x		x	14	4
	Unforeseen events															x						3	12
	Unforeseen conditions																		x			3	12

Table 2.4. Estimating factors contributing to cost underestimation for tunnel projects (continued).

	Factors	Science Direct							Others														
Project Specific Factors	Nature/type and length of project implementation		x			x		x	x			x										8	7
	Size of project					x			x											x		8	7
	Geological/ground conditions	x		x	x		x	x				x			x			x		x		18	2
	Support requirements				x			x													x	7	8
	Environmental requirements		x	x			x					x			x			x		x		12	5
	Site investigation																			x		2	13
	Excavation method			x	x		x	x												x	x	8	7
	Safety						x					x						x			x	6	9
	Changes on project specs and design						x					x	x									4	11
	Tunnel diameter							x												x	x	4	11
	Tunnel length							x												x	x	5	10
	Depth of overburden			x																x	x	4	11
Other Factors	Type of project ownership					x			x													4	11
	Geographical location					x			x		x	x									x	8	7
	Water problems			x																		3	12
	Social issues										x											1	14
	Technological innovation			x		x			x			x	x							x		9	6
	Government standards and regulations		x			x	x	x						x							x	9	6
	Political requirements		x				x	x				x						x	x			8	7
	Local governmental pressures													x								2	13
	Lack of organizational capacity		x						x										x			5	10
	Inexperienced personnel									x							x					3	12

The project specific factor group was considered to be the most prevalent factors that contributed to cost underestimation for tunnel projects. Although project specific had the highest percentage of influence, it had two top factors which was the same for the internal factor group while the external group had one factor among the top five factors. The other factor did not have cost estimating factor. The internal factor group had engineering and construction complexities, poor estimation, scope changes, and contract document and conflicts in that order. Project specific factor group had geological conditions, environmental issues, size of project, project implementation duration, and excavation method-from the highest to lowest rank in this category. External factor group had economic and market conditions, project scope, and effect of inflation. For the other factor group, it had technological innovation, government regulations and policies, political issues, and geographic location in that order.

Categorizing of factors provided additional insights into the estimating factors contributing to cost underestimation which would not have been possible with a simple list of factors. Many of the past studies have focused on one or two factors that contribute to cost underestimation for tunnel projects. In this work, a collaborative effort has been taken to gather the most of the factors. The study was aimed at identifying factors and not a particular category contributing to tunnel cost underestimation to help agencies and practitioners to incorporate to develop appropriate cost estimation programs.

2.5.2. Statistical analysis of the estimating factors driving cost underestimation

Table 2.5 lists the estimating factors that contribute to cost underestimation for transportation tunnel projects. The estimating factors driving cost underestimation for the present work was analyzed using descriptive statistics (Minitab Inc., 2013). The distribution and normality of the identified estimating factors were also examined. Statistical analysis was conducted to investigate the mean, standard deviation, kurtosis, skewedness, histogram, and normality plots of the identified factors. The basic descriptive statistics and the Anderson-Darling statistic test were performed on the count data for all 40 factors that contributed to cost underestimation by using the Minitab software program. The descriptive results for all 40 estimating factors were a mean of 6.0, a standard deviation of 4.57, kurtosis of 1.6, and skewedness of 1.38.

The descriptive statistics show that the estimating factors have a high level of skewness at 1.60 and a standard deviation of 4.57. The standard deviation and skewedness figures are high and indicate greater variability for the estimating factors that contribute to cost underestimation. Generally, the underlying assumption is that the data are normally distributed. In this case, normality is examined by plotting the data, checking for kurtosis (how sharp the peak is) or skewness (if more than half of the data are on one side of the peak), or using the Anderson-Darling (AD) statistic test. The hypotheses for the Anderson-Darling statistic test are as follows: H_o: the data follow a normal distribution, and H_a: the data do not follow a normal distribution. The AD test was performed at the 95% confidence level, and the p-value was less than the chosen α-level of 5%. Results from the AD test showed that the factors have a high AD value of 1.8; therefore, the null hypothesis was rejected. Table 4 presents a summary of the top 18 estimating factors that contribute to cost underestimation for transportation tunnel projects with a count of 5 or more.

Table 2.5. Summary of factors contributing to cost underestimation for tunnel projects.

Factors	Description
Engineering and construction complexities*	Engineering and construction complexities are caused by the location or purpose, leading to challenges in the initial design work. (Einstein, 1996; Haas and Einstein, 2002; Donnell, 2005; Shane et al., 2009; Schexnayder et al., 2003).
Geological/ground conditions*	The geology of a site will affect the overall cost estimate for the project. Data obtained from site investigation are in the geotechnical baseline report (GBR) and geotechnical data report (GDR) in the bid documents. These data are used to select the appropriate excavation methods and support systems to suit the soil/rock conditions present (ITA Working Group, 1988; Nilsen and Ozdemir, 1999; Federal Highway Administration [FHWA], 2009).
Poor estimating*	Poor estimating approaches may lead to underestimation of the project cost. The foundation for good estimating is achieved by developing procedures and methods that can be verified to examine errors and omissions in cost estimates (Donnell, 2005; Shane et al. 2009).
Economic and market conditions*	The project's scope and technical complexity determine the number of prospective bidders with the requisite experience and funding (Schexnayder et al., 2003; Donnell, 2005; Shane et al., 2009).
Environmental requirements*	During the project's planning and feasibility stages, long-term environmental requirements must be identified and investigated, and must be appropriately addressed in the environmental studies and design (Flyvbjerg et al., 2003a; FHWA, 2009).
Scope changes	The scope changes can be any discretionary change in size or configuration, including modifications, design alterations, or increases in project elements. They can be controllable or not controllable by the owner and may lead to an underestimation of deliverables or resources (Donnell, 2005; Shane et al., 2009).
Size of project	Project size could be explained by aspects such as diameter, tunnel length, number of tunnels (constructed area), and the time frame required to build the project. The constructed area and the construction time frame are indications for the quantity of items per element used in the project (Songer and Molenaar, 1997; Akinci and Fischer, 1998; Schexnayder et al., 2003).
Technological innovation	Using new "state-of-the-art" technology in terms of new equipment and/or methods of construction that have limited prior application (Schexnayder et al., 2003).
Political requirements	Requirements and restrictions are placed on the project by the communities or owner agencies. Tunnel projects in urban areas are greatly affected by these requirements. The restrictions might include the types of construction methods that can be employed for the work and the hours allowed for work operations (FHWA, 2009).

Table 2.5. Summary of factors contributing to cost underestimation (continued).

Factors	Description
Contract document conflicts	Incorrect contract documentation leads to errors and confusion during the bidding process and later during project execution (Shane et al., 2009)
Excavation method	Tunnel excavation methods include cut and cover, drill and blast, bored tunnelling, the sequential method, and others. FHWA (2009) describes the geological conditions that are suitable for each excavation method (U.S. Army Corps of Engineers [USACE], 1985; FHWA, 2009).
Bias	Bias is demonstrated by the tendency of being over-optimistic about key project measurements. The project parameters are underestimated to ensure that the project remains active in the construction program by the agency estimators or consultants hired by the agency so that the project is within budget (Donnell, 2005; Shane, et al., 2009).
Project scope	Project scope documents the work that is supposed to be accomplished by the project. It also contains the location, size, and budget for the project; and, in some cases, items outside the scope (Schexnayder et al., 2003).
Nature/type and length of project implementation	Nature/type and length of project implementation documents the procedures that may severely impact the quality of the environment, natural resources, and health of a community, and requires compliancy to government standards and regulations (Akintoye, 2000; Schexnayder et al., 2003).
Support requirements	Support requirements describe the procedures and materials used to improve and maintain the load-bearing capacity of rock or soil near the boundary of an underground excavation for both temporary and permanent. Tunnel support systems include shotcrete, steel mesh, timbering, steel concrete lining, or a combination of methods (Hoek and Wood, 1987).
Safety requirements	Tunnel construction is a dangerous undertaking that involves heavy equipment and working in confined spaces underground. In this case, the safety of labour and equipment needs to be addressed. To safeguard the safety of labour from falling objects, being electrocuted and adequate lighting and ventilation provided. Other safety issues, such as water entering the tunnel, must be adequately addressed.
Government standards and regulations	Regulatory constraints for the protection of the natural environment, public health, and safety from the effects of the proposed project control the use of labour or procurement (Donnell, 2005; Schexnayder et al., 2003).
Lack of organization	Lack of organizational capacity between the different disciplines such as contractors, consultants, and other personnel, involved with the execution of the project capacity (Akintoye, 2000; Cantarelli et al., 2010).

*The top-five estimating factors contributing to cost underestimation of tunnel projects are described in the discussion section

2.6. Review Question 2: Cost-Estimation Methods

Review question 2 related to the cost-estimation methods or processes used to calculate the initial estimates for tunnel projects. Thirteen papers addressed this question. Evidence deduced from the literature showed that most methods used to calculate initial estimates are deterministic and do not include the risk that is inherent with tunnel-construction activities. Many methods followed the traditional quantity take-off format termed “provisional” because the quantities are bound to change. The initial estimates prepared by these methods are inaccurate because all project data are not available. Cost-estimating methods from the review that are used to predict the initial estimates for transportation tunnel projects are summarized in the following sections.

The unit price estimation method is characterized by a thorough, in-depth analysis of the project by dividing it into small work items, and a unit price is then established for each item (Dysert, 2003; Peurifoy and Oberlender, 2002). The unit prices are obtained from published books (*BNI, R.S Means,* and *Engineering News Record*), contractors’ quotes, or build-up unit rates. The estimates commence at the lowest level of engineering work, such as engineering drawings, specifications, or the detailed tasks required to accomplish the project. The unit price is then expanded to the needed quantity to find the work item’s cost. All the cost items are then summed to obtain the total estimated cost. The unit-price estimation method provides better credibility than plain judgment as a means of ascertaining the initial cost estimates based on materials, machinery, and labor content.

The capacity-factored method is employed during the project’s screening stage. It is a fast and consistent means of determining whether a proposed project should continue to the next stage (Dysert, 2003). The method can be applied when deciding among different alternative designs. Data used in the capacity-factored method to determine the estimated cost for an alternative design are derived from a project of known scope with similar independent variables. This methodology relies on a nonlinear relationship between the capacity and cost. The method must account for differences in scope, location, and time (Department of Energy [DOE], 2011).

The Judgment method is an estimation process that utilizes experts knowledgeable in that field to establish the project's cost (DOE, 2011). This method is appropriate in the early stages of a project or for class 5, 4, and 3 cost estimates. The method depends on experience and on good judgment and is, therefore, subjective (DOE, 2011). The advantages of the judgment method are as follows: it can be used where no historical data are available for cross checking cost estimating relationships (CERs) that require a lot of data to develop; it takes minimal time; and it is easy to implement. The disadvantages are as follows: it is only used as a last resort; it is risky because one expert controls the discussions and influences other group members; and the approach is not considered to be very accurate or valid as a primary estimating method (DOE, 2011).

The analogy method, also termed the specific analogy method, uses a known cost or schedule for an item to develop a cost for a new project item (DOE, 2011). The new project item's cost is adjusted to reflect the design complexity, location, and other geographical (specific) conditions. This method is employed to compute cost estimates for classes 5 and 3. The advantages of the analogy method are as follows: it can be used before the detailed design is known; the estimate is developed quickly and at a minimal cost; and the method is tied to historical data and, is, thus, readily understood. The disadvantages include relying on a single data point; obtaining detailed cost, technical, and programmatic data to develop the analogy; and being too subjective about the technical parameters' adjustment factors (DOE, 2011).

The parametric-estimating method is a mathematical representation of cost estimating relationships that provide a logical and predictable correlation between the cost as a dependent variable and the cost estimating factors as the independent variables associated with the project being estimated (Duverlie and Clastelain, 1999; Dysert, 2003; International Society of Parametric Analysis [ISPA], 2008). Parametric models are developed by applying regression analysis to historical project data (obtained from past projects). A summary of the different cost estimation methods is presented in Table 2.6.

Table 2.6. Comparative review of cost estimation methods.

Method	Type	Remarks/Comments
Unit-price	Non-algorithmic	Works based on a developed work breakdown structure by dividing the project into small work items. The method being deterministic in nature and with no detailed engineering drawings or specifications for the project might lead to cost underestimation.
Capacity factored	Algorithmic	Applies to a project with similar independent variables. Its success depends on whether the method accounts for differences in scope, location, and times. Otherwise if not considered might contribute to cost underestimation.
Expert judgement	Non-algorithmic	Uses knowledge acquired from past comparable projects together with objective cost estimation techniques. At the feasibility stage because there are no detailed information is available, estimates might not be complete and thus lead to cost underestimation.
Analogy	Non-algorithmic	Works based on an actual cost or a schedule to develop project item costs. It requires data about past projects and in some situations there are no similar projects. Adjustments are required for known differences such size, complexity, scope, duration, etc. if not factored may lead to cost underestimation.
Parametric	Algorithmic	Uses a mathematical relationship between project variables and historical data to predict a cost of a project. The influence of the parameter on cost reflects the size or scope of the project. The method does not account for the number of variables involved and the complex interactions between them that might contribute to cost underestimation.

It is problematic for any organization or individual to accurately arrive at consistent and accurate cost estimates given the myriad of parameters that need to be included. On the basis of the information given in Table 2.6, the various methods described have different challenges and limitations. Hence, it is important to select an appropriate method to use based on the merits of that technique. For transportation tunnel projects, the method utilized to predict cost should take into account the effects of innovations, challenging geographic conditions, environmental, or other unique circumstances. The best that can be expected of such projects is reasonable approximation of costs to reflect the many variables by employing experience professionals.

Consequently, an organization or individual should allow for sufficient time for the preparation of the estimates to avoid the consequences of failure which is often a cancelled project. Even where projects are the same, such as highways, there is a tendency to redesign the next for architectural engineering diversity, technological advances, or other reasons.

2.7. Review Question 3: Cost-Estimation Models

Review question 3 was related to the tunnel cost-estimation models used to compute the initial cost estimates. The currently utilized cost-estimation models are not covered extensively in the literature or in academic circles. In cases where information is available, it is limited in nature (Rostami et al., 2013). Much of the published work on cost-estimation models contains data which are project specific and cannot be applied to other tasks. A summary of estimation models follows.

The probabilistic analysis of cost and time in tunneling (PACT) model was developed by Oreste (2006). PACT requires several factors and parameters to be available before performing a cost-estimation computation. The model needs the tunnel to be divided into the mining and support classes of homogeneous sections (Oreste, 2006). According to Oreste (2006), the following parameters must be identified times of each site operation; mean velocity of advance, starting from the organization of the time table; overall time required to advance for each excavation category; quantity of materials used for each meter of a tunnel and for each excavation category; and total costs for a tunnel, including material, personnel, equipment depreciation, and fixed costs. Identifying these factors and/or parameters might not be possible during the feasibility phase of a tunnel project; hence, it is difficult to use this model.

The Decision Aids for Tunneling (DAT) model was developed by the Massachusetts Institute of Technology and contains two modules: the geology and construction modules. The DAT model is used for the cost estimation of transportation tunnel projects, particularly in Asia and Europe. In the United States, it is rarely used apart from pilot applications. The geology module produces probabilistic geologic/geotechnical profiles that show geologic conditions at a particular tunnel location by considering the uncertainty of the given geologic data obtained by interviewing experts. The data are obtained by subdividing the tunnel geology into zones that correspond to particular geologic units (Haas and Einstein, 2002). The construction module simulates the construction process, relating geologic profiles to construction methods. The construction methods define cross sections, initial support and permanent support, together with the excavation methods suitable for specific ground classes. For each construction method, the associated duration and cost are calculated.

The DAT model was developed to address uncertain conditions during the feasibility phase. The model determines the overall conceptual construction cost estimate and the duration for a tunnel project. DAT considers the time and cost associated with uncertainties as a function of geological conditions, tunnel dimensions, and construction methods (Aoyagi, 1995; Halabe, 1995). The model considers uncertainties during its application (to estimate tunnel costs), and its output could be used as a basis for risk analysis and decision making.

Probabilistic cost estimating, termed the Cost Estimate Validation Process (or CEVP®) is a peer-level reviewed, risk-based approach that was developed by the Washington State Department of Transportation. The model contains different steps to follow throughout the project's development period. The approach includes a base plan and strategy for the project, the associated base-cost estimate, the validation of cost by external experts, and the inclusion of risk in the estimate to produce a probable cost and schedule estimate (Reilly et al., 2011). The risk assessment is factored into and incorporated at all phases of the construction-development process. The CEVP process incorporates three components: cost validation, risk identification, and modelling.

The CEVP process starts with a description of the plan, design approach, strategy, schedule, and project cost at the conceptual stage. The project's description information is supplied by the project team. After this stage, the CEVP team assists the project team with a review of the current cost estimate and modelling. The CEVP process cannot create a project's cost estimate where none exists. Molenaar (2005) reports that the CEVP process involves the following milestones: project identification and preparation, workshop initiation, cost validation and risk identification, integration and model construction, presentation of results, validation of results and generation of alternatives, and implementation and auditing. In order to achieve consistent and valid results, all process milestones must be maintained throughout the CEVP phases.

Most of these models need detailed information and parameters about the tunnel before computing cost estimates. The unpredictability for geological trends or geological formation presents a huge challenge for cost estimation. During the tunnel project's feasibility phase, limited data are available because detailed site investigation has not been done to determine the maximum information about the rock and soil characteristics, structural systems, and groundwater conditions (Hoek, 2001).

2.8. Review Question 4: Risks in Transportation Tunnel Projects

Review question 4 was related to how risks are addressed by the current estimation models when calculating transportation project costs. The PACT, DAT, and CEVP models incorporate risk at different stages of the construction process. The DAT approach was developed to address problems associated with rock formations and has limited applications with soft soils. There are ongoing studies trying to determine the best ways to incorporate other types of soils, apart from rock formations, with the approach. The CEVP method incorporates risk assessment at all stages of the construction process. WSDOT currently uses the approach to evaluate cost and to schedule state projects. All the described models address the problem of risk for transportation tunnel projects, but the biggest challenge is identifying risks at the feasibility phase due to the project's broad definition.

2.9. Discussions

As unpredictable as the change in cost and costing of a tunnel project is and as inevitable as the entire process of costing and the change inherent in it are, a major area attached to major projects where cost is concerned is cost change predictions. Estimates are made but change is inevitable. So modifications in initial estimates are always both unavoidable and admissible but to some extents. Before the presentation of the important factors from analyses done on the factors, it should be noted that the aim of this section is to discuss the top five factors contributing to tunnel cost underestimation. Although estimating factors such as scope change have been identified as influential factors, they are not discussed because they were not among the top five. Equally, possibilities that some factors may be related such as safety to government standards and complexity, or contract documents may be related to size of project and innovation and type of project implementation, or the interplay between these variables; they are not addressed in the present work. A discussion of the top-five cost estimating factors contributing to cost underestimation for transportation tunnel projects follows.

2.9.1. Engineering and construction complexities

Engineering and construction complexities triggered by the project's location or purpose lead to challenges for the initial design work. Engineering and construction complexities could be defined by the size and implementation of the project which will lead to complex plans, cost estimates, and schedules. It is also possible that problems about the means and methods of the project's constructability might arise among different disciplines working together during the planning and design phases (Donnell, 2005; Einstein, 1996; Haas and Einstein, 2002; Shane et al., 2009; Schexnayder et al., 2003).

The complexities being referred to are utility complications, difficulty dealing with rights-of-way (ROW), dealing with stakeholders for which there is no leverage, structural design complexities, construction staging, and traffic management. Utility complications occur when utilities are within the highway ROW and do not follow established minimum requirements for location, method of installation, adjustment, and maintenance of facilities. Relocating utilities requires high costs to acquire the new ROW and has the potential for increased environmental impacts. Typically, a right-of-way is purchased later in the design stage, and objections to ROW appraisal take a lot of time and/or money to resolve (FHWA, 2009). Thus, utility relocation may not happen in time.

Stakeholders need to be identified and need to be continuously engaged early in the project phase. The partner agencies and the public should hold early sessions to identify concerns and opportunities in order to address the issues about engineering and construction. It is difficult to accommodate all inputs from project stakeholders without backtracking, which is common for project-development processes.

Structural-design complexities could arise from a lack of detailed site investigations to obtain information about the project and the cost involved. In fact, Parker (1996) notes that there is no guarantee that any geotechnical task will provide sufficient information for tunnel design, even if the project is properly planned and executed well. Also, there could be concerns about the coordination of personnel from different firms involved with the design process.

Construction staging, or a temporary storage area, is required; tunnel-construction activities can be executed from there. Adequate space is needed to accommodate contractors' offices, equipment and materials, muck stockpiles, electrical substations, and many other needs. The availability of space is necessary to locate structures and material storage, and to allow the free flow of materials and equipment into and out of the tunnel (FHWA, 2009). Property acquisition to house these facilities might be more expensive initially, but overall, this step may improve tunnel productivity, lower costs, and provide an opportunity for the owner to sell extra property after tunnel completion (FHWA, 2009). A construction staging area must be acquired earlier to avoid a disruption for the tunnel's construction operations. A traffic-management plan must be developed and agreed to by all stakeholders in order to facilitate tunnel-construction work and to minimize disruptions for people traveling along the route. These concerns need to be sorted and addressed when preparing cost estimates by providing appropriate contingencies to address the issues that could result to cost underestimation. Tunnel dimensions, the site location, soil conditions, and multiple stakeholder interfaces require innovative technological solutions. We can assume that adequate space will be available to accommodate construction complexities, such as construction staging and other associated construction operations. For engineering complexities, it is wrong to assume that the geology will provide the required structural strength. A thorough site investigation must be undertaken to ascertain geological trends, or geological formations present, for design purposes.

2.9.2. Subsurface conditions

Geological/ground conditions are cited as a cause of cost underestimation for tunnel projects (FHWA, 2009; ITA Working Group, 1988; Nilsen and Ozdemir, 1999). Natural soils are generally heterogeneous and are highly variable in their properties. Major problems with ground conditions are caused by water permeation; fault lines; very soft soil that will not support the tunnel-boring equipment; and the variation from soft sand, or gravel, to extremely hard rock (FHWA, 2009). Difficult geologic conditions could translate into higher construction costs; conversely, favorable ground conditions can reduce the construction costs. Geological and geotechnical engineering studies are termed “site investigation.” Site investigation is a thorough process that encompasses surface and subsurface exploration to collect data for safe and economic design, a feasibility study, and a project’s cost estimation. Site investigation is important for underground work because results from the investigation could affect every major decision about the proposed infrastructure project. Nilsen and Ozdemir (1999) reported that site investigation and testing are crucial for an underground infrastructure project because they provide the basis for planning the overall design, defining the project’s feasibility, analyzing stability and support requirements, evaluating alternative excavation methods, selecting equipment and predicting performance, assessing the environmental impact and the disposal/use of excavated material, estimating the costs and schedule as well as preparing tender documents, and analyzing risk. The unpredictability of geological trends, or formations, presents a challenge for the design and construction of tunnels. There are challenges about the number and type of geotechnical tests to conduct in order to provide an accurate indication of rock formation and trends underground. Accurate predictions reduce the risk associated with construction and provide engineers with knowledge about the conditions to expect, enhancing engineers' ability to choose the best tunnel type, design, and construction methods.

Different parties involved with underground construction have prepared general guidelines for designing transportation tunnel projects (ITA Working Group, 1988; U.S Army Corps of Engineers [USACE], 2001; FHWA, 2009). With most of these guidelines, the planning aspect of a tunnel project is identified as a critical component and requires a lot of attention when considering the participation of different disciplines. The guidelines are outlined in the U.S. Army Corps of Engineers' *Engineering and Design Tunnels and Shafts in Rock Manual* (1997), the ITA Working Group's *Guidelines for the Design of Tunnels* (1988), the U.S. Army Corps of Engineers' *Engineering and Design Geotechnical Investigations Manual* (2001), and FHWA's (2009) *Technical Manual for Design and Construction of Road Tunnels: Civil Elements Manual*. A thorough site investigation of the geology, hydrology, and geochemistry cannot be over emphasized because it provides data to compare alternatives as well as the overall selection of means and methods. Therefore, it is important that underground conditions be thoroughly investigated and addressed for any planned tunnel project.

In-situ and laboratory tests need to be conducted on both soil and rock formations to determine the behavior of the rock and the soil surrounding the tunnel. Geotechnical tests and procedures are described by FHWA (2009). Tunnel construction is largely a function of excavation considerations and ground-support requirements that are determined from the geotechnical baseline report (GBR) and geotechnical data report (GDR) that form part of the bid documents. Complexity and underground conditions make it difficult to find an accurate estimating process to utilize.

2.9.3. Cost estimation

The cost-estimation process for transportation tunnel projects is very complex and challenging. The approaches used to calculate early construction costs for tunnel projects are covered in question 3. The approach and procedures need to be understood, checked, verified, and corrected (Schexnayder et al., 2003). Cost estimation is defined as a process that is used to compute the quantity and price of the resources required to determine the early estimate for engineering and business decisions (Association for Advancement of Cost Engineering [AACE] International, 1998, DOE, 2011). Risks and uncertainties associated with an estimate must be addressed. Primarily, initial estimates are used as inputs for budgeting and for forecasting the construction costs when the decision to proceed is made (Flyvbjerg et al., 2003b). Project owners use estimates to look for ways to control huge infrastructure project budgets from the pre-construction phase to final completion. It is, therefore, imperative that accurate initial costs be calculated. The early costs form a fundamental component for a project to be implemented successfully.

Information from the literature shows that, currently, no transportation-industry standard guidelines are available for estimators to follow when computing initial estimates for transportation tunnel projects. Individual companies are at liberty to formulate and define their estimate type and percentage of contingency to apply to the initial estimates (Peurifoy and Oberlender, 2002). A commonly cited industry standard is the classification system developed by the Association for Advancement of Cost Engineering (AACE) International termed 18R-97. This standard classifies cost estimates into five classes as shown in Table 2.7 (AACE, 1998).

Projects with the lowest definition level are categorized as class 5, and projects with detailed engineering designs are categorized as Class 1. The guidelines establish an expected accuracy for an initial cost estimate that corresponds with the project's definition level.

Table 2.7. AACE International cost-estimate classification system.

Estimate Class	Level of Project Definition	End of Usage Typical Purpose of Estimate	Expected Accuracy Range
Class 5	0 - 2%	Concept screening	-50% to +100%
Class 4	1 - 15%	Study or feasibility	-30% to +50%
Class 3	10 - 40%	Budget, authorization, or control	-20% to +30%
Class 2	30 - 70%	Control or bid/tender	-15% to +20%
Class 1	50 - 100%	Check estimate or bid/tender	-10% to +15%

Sourced from AACE International RP No. 18R-97: Cost Estimate Classification system: As Applied in Engineering Procurement, and Construction for the process Industries (AACE, 1998, DOE, 2011).

AACE guidelines use both deterministic and stochastic methods, depending on the level of project definition. For a low level of project definition, stochastic methods are used to develop cost estimates (Dysert, 2003). At this definition level, cost drivers that could have a significant impact on a project's cost must be identified. Then, a model, based on the identified cost drivers, is developed. Deterministic methods are most applicable at higher levels of project definition. Stochastic estimating methods are not commonly used to calculate cost estimates for transportation tunnel projects as compared to those methods that utilize historical unit costs. There is a paucity of specific data and a breakdown of data associated with transportation tunneling work because these projects are comparatively rare in comparison to bridges and other transportation projects where unit-price data are more available. Finding accurate and comparable data about costs for transportation tunnels is difficult because data might have been distorted.

A project's cost estimates can be either approximate or detailed, depending on the level of project definition (Dysert, 2003; Peurifoy and Oberlender, 2002). In general, initial cost estimates for transportation tunnel projects are approximate. During the feasibility stage, detailed estimates are difficult to prepare due to the complex nature of engineering work and the technological changes. In recent years with the use of computers, researchers have developed cost-estimation techniques that could be used to predict cost estimates to address concerns related to detailed technical information. These methods are effective for situations where a logical relationship exists between the cost as the dependent and the independent variables (design parameters or physical-characteristic data used to develop cost-estimating relationships) (Dysert, 2003; Ostwald, 2001). The mathematical models developed from independent variables, termed "cost drivers," are then used to establish the cost estimates. The advantages of the parametric-estimating method are as follows: fast and effective, easy to justify, simple to use, empirical by nature, and repeatable and objective. The disadvantages include the following issues: the cost estimate is an aggregate with no details; there is no way of knowing if the past and present methods are the same; parameters that are not included could become important; and it is difficult to develop the model because it requires data collection, evaluation, and validation; that are critical in the parametric-estimation process. Among the approaches employed include stochastic, deterministic, or a combination of the two methods to determine the conceptual cost estimate for a tunnel project.

2.9.4. Economic and market requirements

For economic and market conditions, the scope and technical complexity of a project influence the number of prospective bidders (with the required experience and funding). The project's size and scope determine the number of contractors who can bid for the work (Schexnayder et al., 2003). Transportation tunnels are unique and large, making it difficult for small or even large contractors to bid and necessitating joint ventures for the contractors. The joint ventures result in a lack of competition among contractors in the market, and the impact is increased tunnel costs because the contractors are not aggressive with their bids. Funding is needed for bond and other financial requirements.

Large projects are prone to risks and affect the estimation methods for project costs. The tunnel projects stretch available resources to the limit, have a high profile with political subdivisions and the public, are noticed by regulators, take a long a time to complete, and are less likely to maintain continuity of management (Schexnayder et al., 2003). Transportation tunneling work is unique when compared to other types of civil construction work. Civil construction work is different from other projects because a problem at one location will not affect construction operations performed simultaneously at multiple locations. In the case of a transportation tunneling project, it is difficult to perform work at multiple locations because of the tunnel's geometry (FHWA, 2009). Tunnel work involves repetitive operations.

2.9.5. Environmental issues

Environmental requirements need to be addressed at the project's planning and feasibility stages. Long-term environmental requirements must be identified, investigated, and appropriately addressed at the environmental study and design stages. The environmental requirements, when implemented, must address the reconstruction of local communities; historic sites (protected areas, bird-nesting areas, and fish- and frog-hatching areas); wetlands; and other aesthetically, environmentally, and ecologically sensitive areas (FHWA, 2009; Flyvbjerg et al., 2003a). Stakeholders could streamline the environmental review to accelerate diversity during the feasibility stage of a transportation tunnel's design. The various stakeholder groups should be well coordinated to avoid conflict. Poor coordination might result in the exclusion of key stakeholders for tunnel projects, leading to resentment or antagonism.

Environmental costs associated with clean-up, removal, and disposal of muck or other wastes need to be determined. Environmental issues, such as wetlands, bird nesting, and others, also have restoration costs. The costs associated with control measures to address mitigation against environmental impacts around the tunnel need to be included.

2.10. Limitations and Future Work

The papers reviewed were limited to a selected sample of databases. An analysis of the frequency of estimating factors contributing to tunnel cost underestimation in a particular category was inadequate due to the sample size and the selection process. The four categories or groups developed were neither mutually exclusive nor definitive. A lack of quantification for geotechnical uncertainty might have also played a role.

The present approach is different from others because it has not been used in the industry. This initial study forms a base design that can be rolled out into other construction projects to determine the factors affecting cost estimation of projects in the industry.

2.11. Summary

Estimating the cost of transportation tunnel projects during the feasibility stage is very complex and challenging for state/federal agencies. The use of traditional methods to estimate tunnel project costs has led to significant underestimation of tunnel projects because of limited information and data to compare different alternatives. To address cost underestimation, a systematic review on estimating the cost of transportation tunnel projects was conducted by exploring cost estimating factors, methods, models, and risk/uncertainty. The need for systematic investigation of the literature is important because to date no review of literature has been conducted on the subject of estimating the cost for tunnel projects. In fact, there is need to review cost estimation for tunnel projects in terms of the research that has been conducted in the past.

The study identified, categorized, analyzed, and synthesized cost estimating factors that need to be addressed by state /federal agencies and metropolitan planning organizations in order to effectively compare cost estimates for tunnel projects. Incorporating estimating factors could help state/federal agencies and metropolitan planning organizations in improving the accuracy of tunnel cost estimates. In order to obtain primary studies, 7 databases were searched based on pre-established criteria. Overall, out of 788 studies found in the databases, 39 primary studies from 1988 to 2013 were selected and evaluated based on the selection criteria. A total of 40 estimating factors were identified from the systematic literature review as contributing to cost underestimation and were categorized into four major groups: external, internal, project-specific, and other factors. The project-specific group had the highest level of influence at 36%.

The findings from the analysis indicate that organizations should not consider project-specific group estimating factors alone when preparing estimates. Obviously, state/federal agencies and metropolitan planning organizations need to address cost estimating factors including the top-five factors contributing to cost underestimation such as engineering and construction complexities, geological conditions, cost estimation, market conditions, and environmental requirements. The research posits that organizations need to focus on the estimating factors in order to be competitive because they are consistent with findings from the systematic review as well as other infrastructure projects. Although not all estimating factors will apply to each tunnel project, it is important that applicable factors be determined and addressed.

The research compared different methods, current models, and how the models address risk when estimating cost for tunnel projects. Findings from the review questions showed that most cost estimation methods used to calculate initial estimates are deterministic and do not incorporate risk/uncertainty which is common in underground construction work. Therefore, cost estimates prepared using these estimation methods are inaccurate since all project data were unavailable. The cost estimation models currently in use were developed based on project-specific data and may not be applied to other projects. The models reviewed were the PACT, DAT, and CEVP. The models cannot produce accurate estimates due to the unpredictability for the geological trends and require a detailed site investigation; a step not possible during the feasibility phase. The PACT, DAT, and CEVP models account for risk. Although the models address risk when calculating cost estimates, the biggest challenge is risk identification during the feasibility phase because of the project's broad definition. The results from the review questions provide a body of knowledge that can help state/federal agencies to design and implement successful cost estimation programs.

CHAPTER 3. PARAMETRIC COST ESTIMATION RESEARCH PARADIGM

3.1. Introduction

This chapter of the dissertation proposes the overall research paradigm, hypothesis, and the procedure for developing a parametric cost estimation function for transportation tunnel projects. The research involved collection of pertinent qualitative and quantitative data that was used to develop a parametric cost estimation function for transportation tunnel projects to predict conceptual estimates. The cost estimation function for transportation tunnel projects generally consists of a number of physical parameters associated with the tunnel. In this study, a systematic literature review identified influential parameters used to develop the cost estimation function. The research consists of hypothesis formulation and evaluation, research design, data collection, and data analysis. A cost estimation model termed parametric cost estimation function is then developed by correlating the parameters to tunnel project costs. Finally, the developed function is used to perform case studies to investigate cost estimates for chosen tunnel projects, and to gain management insight on how tunnel costs fluctuate due to risks and uncertainties.

3.2. Research Approach

The overall framework used to develop the parametric cost estimation function is depicted in Figure 3.1. The parametric function development consists of problem definition, identification of cost drivers, formulation of hypothesis, research design, preparing survey instruments, Institutional Review Board (IRB) approval, conducting survey, coding of research survey results, data analysis, regression analysis, discussion of results, and performing case studies. Problem definition and identification of cost parameters was covered in Chapter 2 of the dissertation.

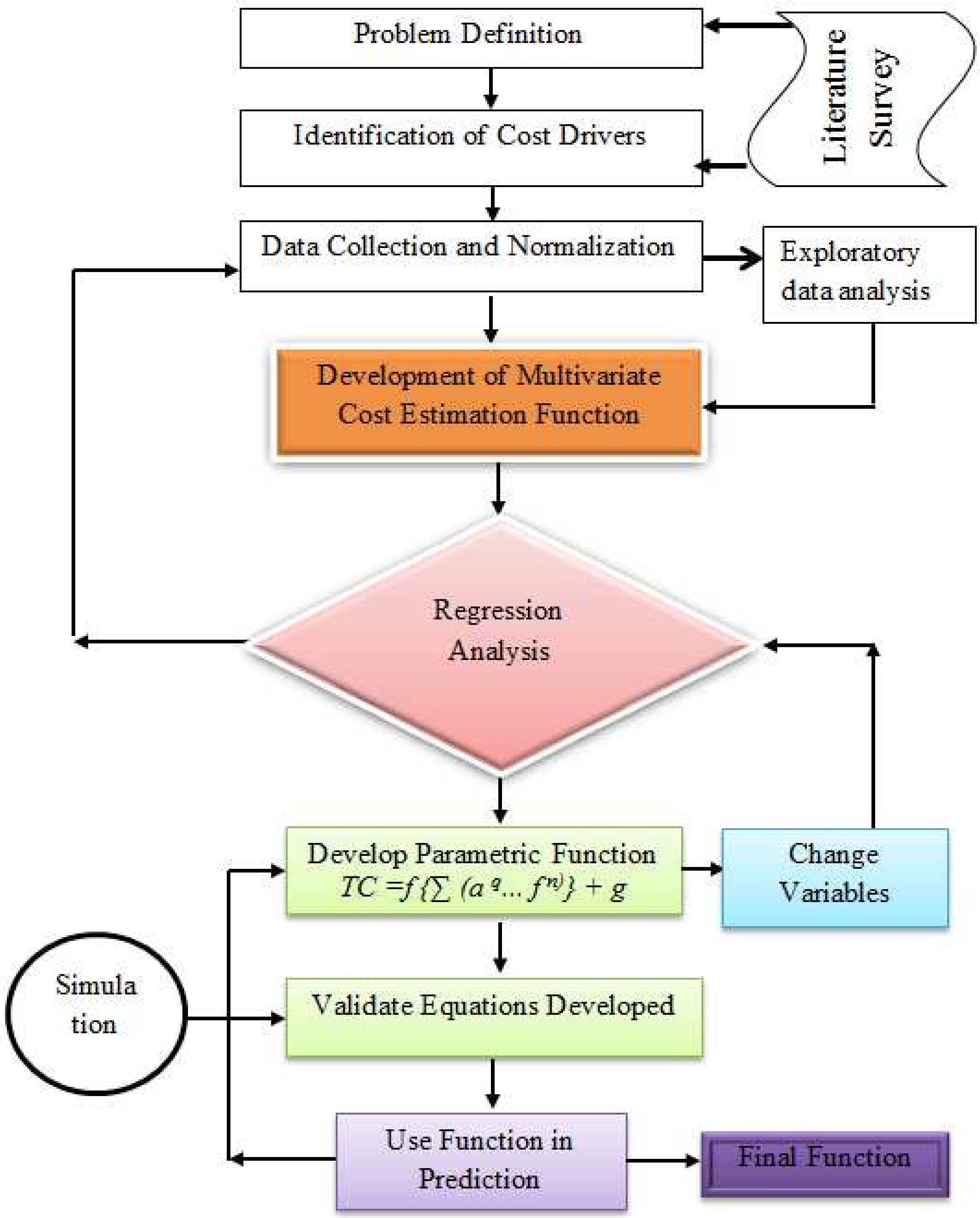

Figure 3.1. Procedure for developing a parametric cost estimation function

$$Tunnel\ Cost, \quad TC = f\left(a^m \Theta b^n \Theta c^o \Theta d^p \Theta e^q \Theta f^r\right) + g$$

Where *a*, *b*, *c*, *d*, *e*, and *f* are cost drivers; *g* = error; *u*, *n*, *o*, *p*, *q*, and *r* are power indices to account for risk and uncertainty, and Θ = operator (+, -, %, *) The rest of the sections are organized as follows: Section 3.3 presents hypothesis testing. Section 3.4 describes the proposed research method and design. Section 3.5 discusses data collection, processing and analysis. Section 3.6 presents the theoretical selection and derivation of the cost estimating relationships (CERs). Section 3.7 discusses the theoretical aspect of the development of a parametric cost estimation function.

3.3. Hypothesis Testing

This section formulated the hypothesis, which was the main focus of the study using statistical analyses. The main hypothesis developed out of what was deemed important from the systematic literature review in order to understand the factors impacting cost underestimation of tunnel projects. The formulated hypothesis was evaluated using Minitab statistical program. The hypothesis is explained.

Hypothesis: The possibility of a relationship between tunnel variables and the tunnel construction cost exists.

H_0: There is no dependency/correlation between identified cost variables and cost estimate of a tunnel project.

H_1: There is dependency/correlation between identified cost variables and final cost estimate of a tunnel project.

The research hypothesis posits that factors (internal, external, project specific, and others) contribute to cost overrun of tunnel projects and predetermines a set of variables for this research. It is important that variables that describe the tunnel and its cost are identified and selected. The selected variables must be measurable for any new tunnel project. Transportation tunnel project cost estimate is considered a dependent variable resulting from the correlation of the independent variables. The factor groups -internal, external, project specific and others contributing to cost overrun in transportation tunnel projects-are treated as independent or cost drivers, because they affect the results. A systematic literature review was used to identify the potential cost factors (Stewart et al. 1995). This research hypothesizes that a relationship exists between identified cost drivers and the final cost of a tunnel project. After analyzing the relationship between the independent and dependent tunnel project variables, the overall conceptual cost estimation function/framework may take any form from numerous mathematical relationships: linear curves, power curves, exponential, or logarithmic curves (Stewart et al., 1995). The new cost estimation function hypothesized has multiple variables and its proposed conceptual framework takes the form given in Equation 3.3.

$$Tunnel\ Cost, TC = f\left(X_1{}^m \Theta X_2{}^n \Theta X_3{}^o \Theta \ldots\ldots X_{N-1}{}^q \Theta X_N{}^q\right) + \varepsilon_i \tag{3.1}$$

Where tunnel cost (TC) is dependent on $X_1, X_2, X_3 \ldots\ X_{N-1}, X_N$ which are cost drivers as shown in Table 3.1; ε_i = error; *m, n*, *o*, *p*, *q*... are power indices involved in the particular variable, and Θ = operator (+, -, %, *).

Based on this hypothesis, 13 predictor variables were selected. Table 3.1 presents the relationship between group factors and variables, quantification measurement, references, and lists the survey question that measures each variable. It is important to test the hypothesis about dependency/correlation between identified cost variables and the initial cost estimate of a tunnel project.

Table 3.1. Predictor variables, quantification measurement, and references.

Group factors	Predictor variable	Units	Reference
Project specific, X_1	Geological/ground conditions	MPA, psi	Nilsen and Ozdemir, 1999; FHWA, 2009
Project specific, X_2	Environmental requirements		Flyvbjerg et al., 2003; FHWA, 2009
Project specific, X_3	Tunnel length	Feet/meters/ miles	De Place, E. (2009)
Project specific, X_4	Tunnel diameter	Feet/meters	Shane et al., 2009; De Place, E. (2009); Schexnayder et al. 2003
Project specific, X_5	Project implementation duration	Days/years	Shane et al., 2009; Schexnayder et al. 2003
Project specific, X_6	Excavation method		USACE, 1985; FHWA, 2009
Project specific, X_7	Depth of burial	Feet/meters	De Place, E. (2009)
Project specific, X_8	Support requirements		Hoek and Wood, 1987

3.4. Data Collection, Processing, and Analysis

3.4.1. Instrumentation

A survey instrument was designed involving Steps 2 to 6 (Figure 3.1). In Step 2, a draft questionnaire was developed based on the systematic literature review conducted for factors contributing to cost underestimation in tunneling projects. The draft was then shared with consultants, professionals in highway construction industry, and other professionals in MPOs as well as in colleagues in academia. The input of these professionals was incorporated in the survey instruments. A pilot study was conducted to test the instruments, after which the problems identified from the feedback were addressed.

The Institutional Review Board (IRB) approval step 4 (Appendix A) was obtained before the survey instrument was sent to potential responders. The participants in this study were professionals in the transportation industry (DOTs, MPOs, contractors, and consultants) as well as a number of professionals in academia. The criterion used to select participants was based on their involvement or participation in estimating initial costs for tunnel projects. The survey instrument was then sent to participants together with a brief description of their rights step 5 (Appendix B).

3.4.2. Data collection and normalization

After identifying cost variables, designing survey instruments, and the approval of the instruments by IRB, the next step was data collection. The data collection was an important exercise because the accuracy of the resulting parametric function (ability to predict future costs) was dependent on the reliability of the historical data. The data was collected using a standard survey instrument. Collecting cost data and information related to cost estimation for tunnel projects was a difficult task because the construction firms were unwilling to share their cost data because most firms believe withholding such information usually gives them an edge in the competitive market. The survey was conducted as per the approved IRB documents and sent out by mail to 39 organizations (22 DOTs, 3 MPOs, and 14 consultants) from April 1, 2014 to July 6, 2014. The response rate for the initial survey was 3 participants representing 8%. The return rate was minimal and a second survey was sent over email targeting consultants and professional in academia involved in tunneling research. In the second survey, two professionals Dr. Jamal Rostami and Mahmoud Sepehrmanesh of Pennsylvania State University and New Mexico Tech respectively responded and emailed a spreadsheet database they had developed. The database was jointly maintained at Penn State University and New Mexico Tech by the researchers (Rostami et al. 2012). The tunnel cost database was developed from information collected from project managers, professionals in academia, and other construction industry players through a questionnaire survey.

3.5. Selection and Derivation of the Proper CER

In the present study, the selection of tunnel variables was identified through a systematic literature review covered in Chapter 2. Generally, the development of a parametric cost estimation function follows: selection of tunnel variables, data collection and normalization, CER form selection and derivation, and testing the function. Cost data was empirically fitted to form a cost estimating function using one of the numerous mathematical relationships. It can take any form including linear curves, power curves, exponential curves, or logarithmic curves (Stewart et al., 1995). The selection of the proper CER equation could also be determined by plotting the data and observing its distributions using a statistical program.

Statistical criteria and variance analysis techniques are used to test the goodness of fit for any regression analysis. Two of the common techniques used are R-squared (R^2) and the standard error (S.E.). Value of R^2 is an indicator of how well the regression equation fits observed points. An R^2 value of one would indicate that the selected form and the derived equation for CER perfectly predict the tunnel cost. The S.E. measures the average amount by which the actual costs differ from the calculated costs. Other tests that can be carried out to check the accuracy of the developed function include using ANOVA or the t-test, or *F* test.

3.6. Development of a Parametric Cost Estimation Function

Statistical procedures used to develop a function can be parametric or nonparametric. Parametric statistical procedures are based on assumptions of the specific form of the distribution of the underlying population from which the sample was taken. Nonparametric statistical tests on the other hand, require no or very limited assumptions about the distribution or parameters of the population from which the sample is drawn (McClave and Sincich, 2009). For parametric statistics, the problem comprises estimating the parameters and testing hypotheses relating to them. Nonparametric statistics is not concerned with the techniques of estimating the parameters, but with specific hypotheses relating to the properties of the population. Nonparametric methods are not used in statistical analysis because of first, they are considered to be less statistically robust compared to parametric methods due to lack of information about the form of distribution function. Second, nonparametric test results are often difficult to interpret compared with results of parametric tests (Biswas, 1991).

Parametric functions, when well-designed and correctly implemented, can improve the accuracy of project estimates, reduce overruns of budgets and schedules, reduce project proposal costs, and enable consultants and stakeholders to consider different alternatives. In parametric cost estimating methods, there is one dependent variable which is the cost, and two or more independent variables based on the project attributes. In general, the equations can take one of the following forms:

i) *Linear relationships*

$$Cost = a + bX_1 + cX_2 + \dots \tag{3.2}$$

ii) *Logarithmic relationships*

$$Log\ (Cost) = a + b \log X_1 + c \log X_2 + \dots \tag{3.3}$$

iii) *Exponential relationships*

$$Cost = a + bX_1^{c} + dX_2^{e} + \dots \tag{3.4}$$

where a, b, c, d, and e are constants, and X_1, X_2, X_3 …X_n are the performance attributes of a project.

Developing a cost estimating function follows these general steps: selection of cost drivers, data collection and normalization, CER form selection and derivation, and lastly testing the function. Multivariable regression (linear and non-linear) approaches are used to develop the parametric cost estimation function. The cost estimation function consists of multiple variables as described in the section on selection of cost drivers shown in Table 3.1. Forward stepwise regression is used to develop the parametric cost estimation functions. During the development process, the procedure begins with performing normal multiple regressions. If all variables are shown as significant (p-values $<\alpha$), then the process is stopped and, this means that the completed/fitted model is good.

If the significance F is low, but one or more of the p-values for the t-tests are high, forward stepwise regression is used to develop the best function that contains some of the variables as follows.

1. Perform simple linear regressions of tunnel cost (independent, y) vs. each cost driver (dependent, *X*) individually. The X variable with the lowest p-value is selected (for example X_{10}.).
2. Do all possible 2-variable regressions in which one of the two variables is X_{10}.
   - If none of the 2-variable regressions gives low p-values for both X_{10} and the other variable stop and use the model utilizing only X_{10}.
   - If one or more of the 2-variable models gives low p-values for both X_{10} and the second variable, select the model with the lowest p-values (suppose it is the one with X_{10} and X_5.), and go to Step 3.
3. Carry out all possible 3-variable regressions in which two of the three variables are X_{10} and X_5.
   - If none of the 3-variable regressions gives low p-values for each of *X10*, X_5, and the other variable, stop and use the model utilizing only X_{10} and X_5.

- If one or more of the 3-variable models gives low p-values for X_3, X_5 and the third variable, select the model with the lowest p-values and continue to Step 4.

The steps to be followed in the development of initial tunnel cost function are summarized next:

(1) Hypothesize the conceptual function framework relating to initial tunnel cost to the independent variables.

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \ldots + \beta_n X_n + \varepsilon \tag{3.5}$$

(2) The second step is to estimate the model coefficients $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \ldots \beta_n$.

(3) The next step is to specify the probability distribution of ε, the random error component of the function.

Assumptions made: for any given set of values of $X_1, X_2, X_3 \ldots X_K$, ε is normally distributed with a mean equal to 0 and a constant variance σ^2.

(4) Step four is to test how well the function predicts initial tunnel cost. Check R^2.

The function can be tested by:

H_0: $\beta_1 = \beta_2 = \beta_3 = \ldots = \beta_{13} = 0$

H_a: At least one of the model coefficients is nonzero.

Test statistic $$F = \frac{\textit{Mean square for model}}{MSE} = \frac{SS\,(Model)/k}{SSE/[n-(k+1)]} \tag{3.6}$$

Rejection region: For $\alpha = 0.05$, $F > F_{0.05}$

After the global test of the function, t-tests for individual β parameters one is interested in may be conducted.

(5) Check for potential problems in the model and solve them by minimizing violations.

(6) The last step in the development process is to use the model for estimation and/or prediction (Mendenhall and Sincich, 1989).

CHAPTER 4. EXPLORATORY DATA ANALYSIS

4.1. Introduction

This chapter presents a summary of analysis results from the transportation tunnel project data collected and described in Chapter 3. Results of the influential parameters for the modes of transportation tunnel project costs are presented. The parameters used to develop cost estimate function(s) for tunnel projects are discussed. A classification is proposed for the functions developed on how to choose the best function to employ to prepare a tunnel cost estimate. A discussion regarding how the developed function for tunnel cost estimation was tested against the transportation tunnel projects input data to examine the percentage of error is also included. The steps follow the procedure illustrated in Figure 3.1.

4.2. Data Acquisition

The data used in this study were obtained from a database maintained by Dr. Jamal Rostami and Mahmoud Sepehrmanesh of Pennsylvania State University and New Mexico Tech, respectively (Rostami et al. 2012). The database contained 272 tunnel projects consisting of different sizes, applications, locations, and ground conditions from North America. The tunnel cost data consisted of the following tunnel applications: metro, highways, water, waste water, storm water, railways, light rail, oil pipelines, and subways.

For this study, a sub database was established to cover transportation tunnel projects only from the original dataset of 272 tunnel projects for different applications. The new database developed had 79 transportation tunnel projects. The resulting dataset consisted of year of tunnel construction, method of excavation, depth of overburden, soil condition, length, diameter, and project cost. Tunnel project costs were based on year of construction which differs for the different projects.

4.3. Data Normalization

The transportation tunnel data retrieved was compiled into a database. The tunnel cost data consisted of tunnel projects with different years of construction and different locations; therefore, it was necessary to undertake data normalization to account for time, location, site conditions, project specifications, and cost scope. The Engineering News Record (ENR) publishes both the construction cost index (CCI) and the building cost index (BCI) on a monthly basis. The CCI and BCI are applied to general construction costs to adjust for time and potential escalation costs to the year under consideration. The CCI was used to account for the tunnel project's year of construction costs for time by city to adjust them to the base year (March, 2014). This process is an important step in the parametric function development process.

The resulting tunnel dataset was then classified into the following categories: entire dataset, type of geology/ground conditions, tunnel type (application), and tunnel excavation method. The different categories were further divided into subcategories, except for the entire dataset. The geology/ground conditions category was divided into hard and soft rock; the tunnel type into highway, subway, and railway; and tunnel excavation method into tunnel boring machine, cut and cover, drill & blast, and mixed methods. Data analysis was performed on the subcategories and the entire datasets.

4.4. Data Analysis

Data analysis is the process of systematically applying statistical techniques to describe facts, detect patterns, develop explanations, and test hypotheses (Levine and Roos, 2002). It helps in structuring the findings from different sources of data collection. It also provides an insight into a large dataset to make meaningful critical decisions in order to avoid human bias from research conclusions with the aid of proper statistical treatments. It helps to verify whether the hypothesis is valid, reproducible, and unquestionable (Tukey, 1977). Data analysis consists of a number of phases including data cleaning, quality analysis, analysis, exploratory analysis, and knowledge representation (Tukey, 1977). A number of methods are employed in data analysis such as classical analysis, exploratory data analysis, and Bayesian analysis. The methodology used in the present work is the classical approach, which involves data collection, model development (normality, linearity, etc.), analysis, estimation, testing and conclusions.

Exploratory data analysis is used to optimize insight into the dataset, discover the underlying structure, extract important variables, test underlying assumptions, and detect outliers and anomalies. Exploratory data analysis employs a collection of statistical techniques to graphically display and interpret data. Exploratory data analysis is used to understand the data. It involves histograms, scatter plots, cross plots, and descriptive statistics. In the Bayesian approach, scientific, engineering and expert knowledge are incorporated into the analysis by combining the prior distribution of the parameters and the data to make joint inferences and test model assumptions. The classical analysis and exploratory data analysis approaches are employed in this research.

The exploratory data analysis (EDA) approach involves using statistical techniques to understand the data. The EDA employs the measures of central tendency, histograms, and scatterplots. A histogram is a graphical summary of the distribution of data under consideration. The central tendency measures the mean, the median, the standard deviation, and other measures being tested. The scatterplot illustrates the relationship between two variables and reveals whether the two variables are related linearly or non-linearly. The results of the exploratory data analysis for the categories of the dataset are offered, which represent a matrix of parameters identified on tunnel projects. These results were subsequently used in the data analysis phase.

4.5. Analysis of the Entire Dataset

The dataset developed contained 79 transportation tunnel projects. The tunnel projects consisted of modes of transportation such as highway, subway, metro, railway, and light rail projects constructed in the past 35 years. A sample of the dataset for the tunnel projects is presented in Table 4.1.

Table 4.1. Sample of transportation tunnel projects data.

Project	Excavation Method	Depth (m)	Length (m)	Diameter (m)	Cost ($millions)
Project 1	TBM Shield		29.1	5.38	139
Project 2	EPB TBM/ D&B/ NATM	15	4.6	6.3	372
Project 3	TBM	36	9.5	6.56	682
Project 4	TBM	36	7.6	6.56	531
Project 5	EPB TBM/ D&B/ NATM	15	4.6	6.3	372
Project 6	Cut & Cover		3.0	10.5	216
Project 7	Shield TBM, C & C		13.5	6.4	1072
Project 8	Cut & Cover		1.0	5.8	62
Project 9	EPB TBM, C & C	20	5.6	6.86	209
Project 10	Shield TBM, C & C	20	2.3	6.7	181
Project 11	Cut & Cover & TBM		5.0	4.2	246
Project 12	TBM, Cut & Cover	13	8.0	5.8	424
Project 13	Shield TBM, D&B, C & C	10	2.4	6.5	1475
Project 14	EPB TBM & C & C	16	6.0	6.27	252
Project 15	NATM	0	2.5	7.83	314
Project 16	cut & Cover	9	1.0	17.2	48
Project 17	EPB TBM (Lovato)	12	15.6	5.91	86
Project 18	EPB TBM	26	1.0	6.4	34
Project 19	Road header	30	1.2	6.93	23
Project 20	D&B	30	4.3	6.93	110

The following parameters were examined: depth of overburden, tunnel diameter, tunnel length, and the total tunnel cost. The analyses for depth, length, diameter, and total cost for the entire dataset are shown in Figure 4.1. The depth of overburden varies from 0.00 m to 57.00 m analysis of depth for the dataset shows that the average is 18.03 m with a standard deviation of

12.05 m. The median is 17.00 m which shows a deviation from the mean of 18.03 m an indication that the dataset is not normally distributed as shown in Table 4.2.

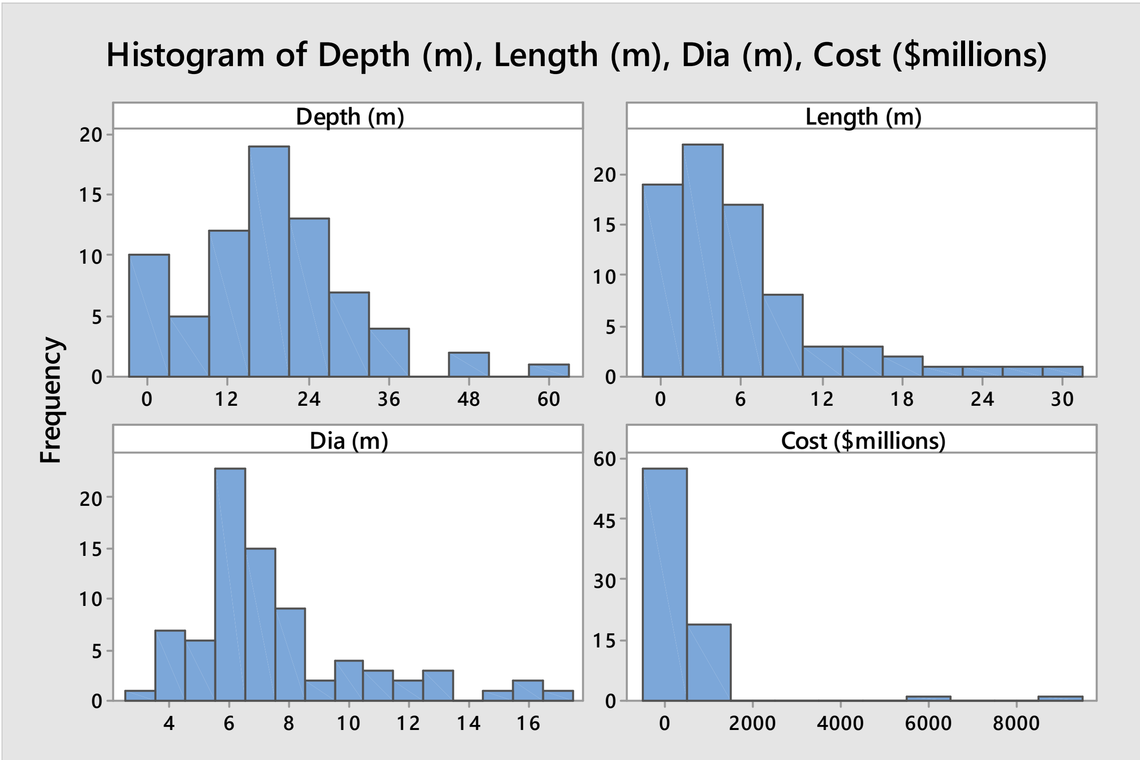

Figure 4.1. Histogram of depth of overburden, length, diameter and cost

Table 4.2. Descriptive statistics for depth, length, diameter, and cost in millions dollars.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	18.03	12.05	0.00	17.00	57.00	0.70	0.97
Length (m)	5.818	6.091	0.960	4.000	29.100	2.05	4.43
Diameter (m)	7.500	2.996	3.250	6.560	17.200	1.47	2.09
Cost($millions)	546	1210	11	246	9090	5.83	37.08

Exploratory data analysis for the length of tunnel shows that the average is 5.818 m with a standard deviation of 6.091 m. The median for the dataset is 4.000 m compared with a mean of 5.818 m. The highest diameter in the dataset was 17.200 m and average and standard deviation were 7.500 m and 2.996 m respectively. The median is 6.560 m compared with a mean of 7.500 m, an indication of the data being left-skewed. Total cost analyses show that the standard deviation is very high at 1,210 million. Other pertinent details for depth of overburden, length, diameter, and cost are presented in Figure 4.1 and Table 4.2.

4.6. Type of Ground Conditions

In the research, the variables identified in the literature review are examined under type of ground conditions in two ways: namely (1) on the basis of tunnel excavation methods, and (2) on the basis of the geology of the subsurface. First, the excavation methods used to excavate transportation tunnel projects were classified as TBM, cut and cover, drill and blast, NATM, and mixed methods. In the mixed tunnel excavation methods group, two or more methods are combined together to excavate the tunnel project. Subsurface tunnels accommodate different modes of transportation such as highways, railways, metros, or subways. Lastly, the geology of the subsurface was divided into hard rock and soft rock and are addressed in the next sections.

4.6.1 Tunnel excavation methods

The data was grouped into tunnel excavation methods and analyzed by investigating the descriptive statistics of each mode of transportation. Table 4.3 gives a summary of the excavation methods used to excavate various modes of transportation.

Table 4.3. Summary of analysis for tunnel excavation methods.

	TBM	Mixed Methods	Cut and cover	Drill and blast
Highways	2	0	8	8
Railways	6	9	2	2
Metro	3	10	4	0
Subways	7	17	4	4

A number of methods are employed in the excavation of transportation tunnels. The following criteria are used for inclusion and exclusion of dataset. Tunnel excavation method dataset must have six or more transportation tunnel projects to be considered for the exploratory data analysis and fitting of the function. Any tunnel excavation method having less than six tunnel projects was excluded. In this section, analyses of the following tunnel excavation methods are performed: cut and cover and drill and blast for the highways category; TBM and mixed methods for railways; mixed methods for the metro category; and TBM and mixed for the subways group. A linear or curvilinear function between the dependent and independent variables is often assumed in literature. In the present work, both linear and curvilinear functions are employed to identify a better fit function for the excavation method(s) of the mode of transportation being examined.

4.6.1.1. Cut and cover method - highways

The cut and cover tunnel excavation method for highways contained eight tunnel projects (Table 1). The parameters analyzed were depth of overburden (De), tunnel diameter (Di), tunnel length (Le), and the total tunnel cost ($ millions). The descriptive statistics of the parameters for the cut and cover method are summarized in Table 4.4 and the histogram representing the parameters is shown in Figure 4.2.

Table 4.4. Descriptive statistics for depth, length, diameter, and cost in millions dollars.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	16.25	7.01	8.00	16.00	27.00	0.48	-1.07
Length (km)	2.826	1.899	1.000	2.384	5.600	0.75	-1.09
Diameter (m)	10.02	4.28	5.60	8.99	16.42	0.77	-0.88
Cost($millions)	432.7	260.8	61.8	410.7	746.5	-0.05	-1.82

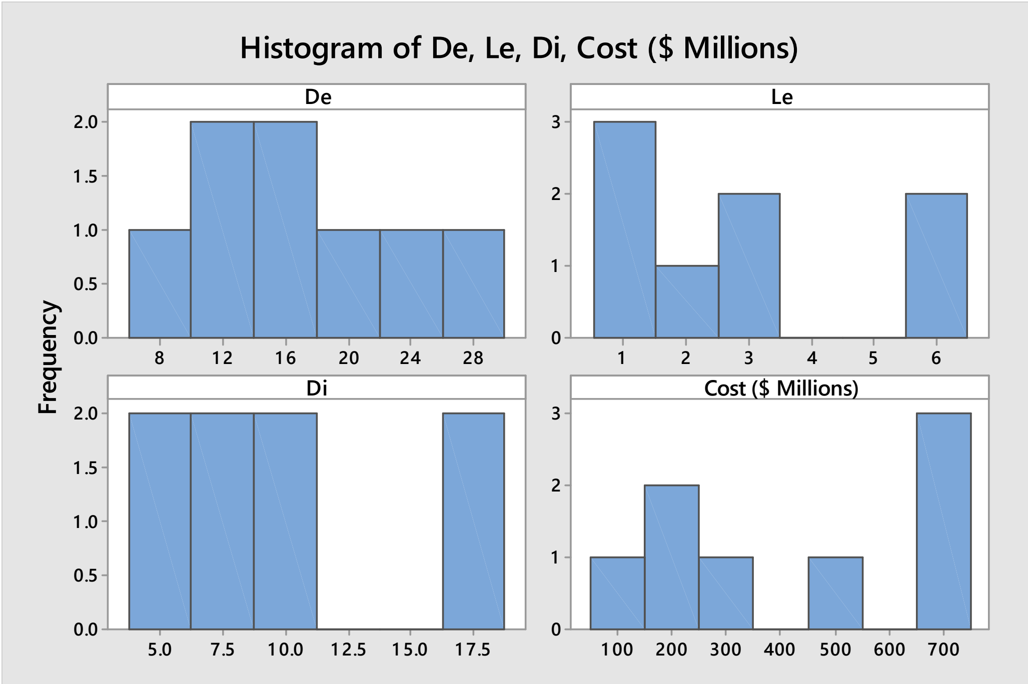

Figure 4.2. Histogram of depth, length, diameter and cost

4.6.1.2. Drill and blast method- highways

The drill and blast tunnel excavation method used in highway tunneling projects had eight data points (Table 4.1). The following parameters were analyzed: depth of overburden, tunnel diameter, tunnel length, and the total tunnel cost. The results of exploratory analyses for the drill and blast tunnel excavation parameters are presented in Table 4.5 and Figure 4.3.

Table 4.5. Descriptive statistics for depth, length, diameter, and cost in millions dollars.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	5.38	9.46	0.00	0.00	27.00	2.11	4.66
Length (km)	2.918	2.153	1.000	2.552	7.240	1.18	1.36
Diameter (m)	7.619	2.464	4.600	6.870	11.060	0.50	-1.32
Cost($millions)	182.5	248.1	11.2	82.8	733.5	1.99	3.71

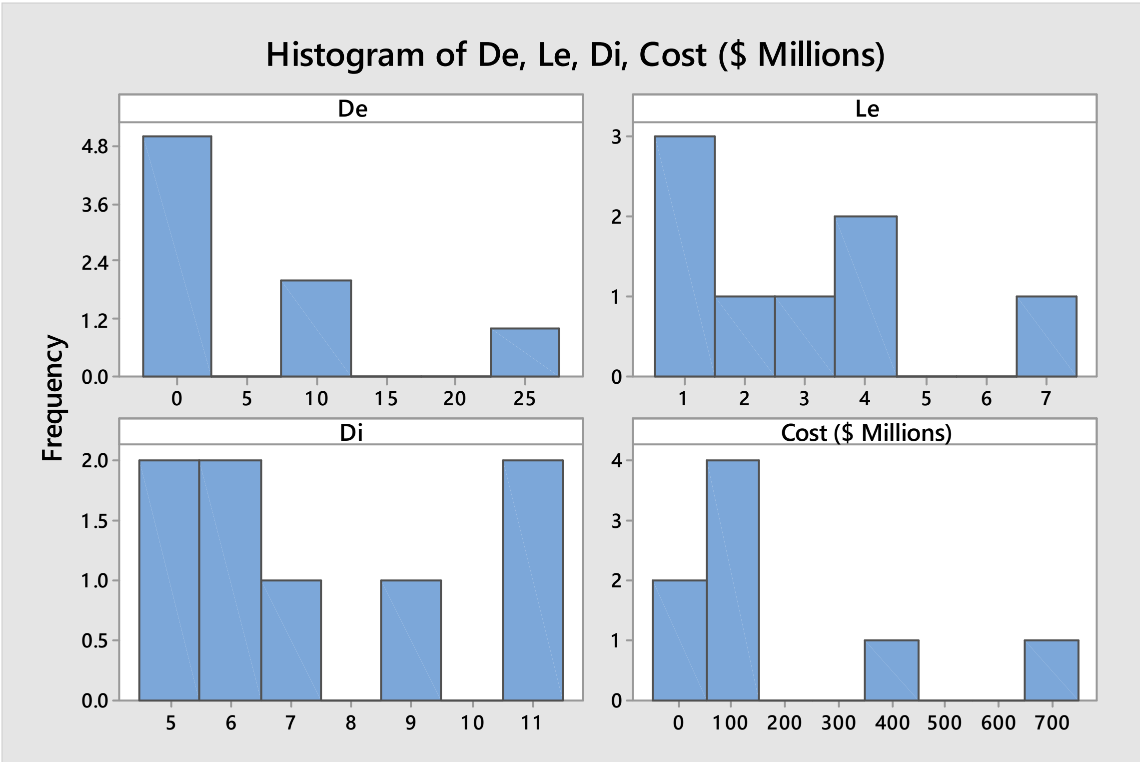

Figure 4.3. Histogram of depth, length, diameter and cost

Curve fitting plots of the dependent variable (tunnel costs) against the independent variables (diameter, length, and depth) for the two highway tunnel excavation methods performed. The curves are presented in Figures 4.4 to 4.6. The figures show the plots of cost against diameter, length, and depth of overburden for both cut and cover and drill and blast tunnel excavation parameters. Subsequently, Tables 4.6 to 4.8 present the summaries of the fitted equations for the two highway tunnel excavation methods.

Table 4.6. Summarized fitted curves for cut and cover and drill and blast excavation methods.

Excavation Method	Data points	R^2	Equation fitted to the curve
Cut and cover	8	0.58	Cost = $1.6382D^3 - 54D^2 + 595.56D - 1749.6$
Drill and blast	8	0.34	Cost = $11.845D^3 - 259.7D^2 + 1815.5D - 3929.8$

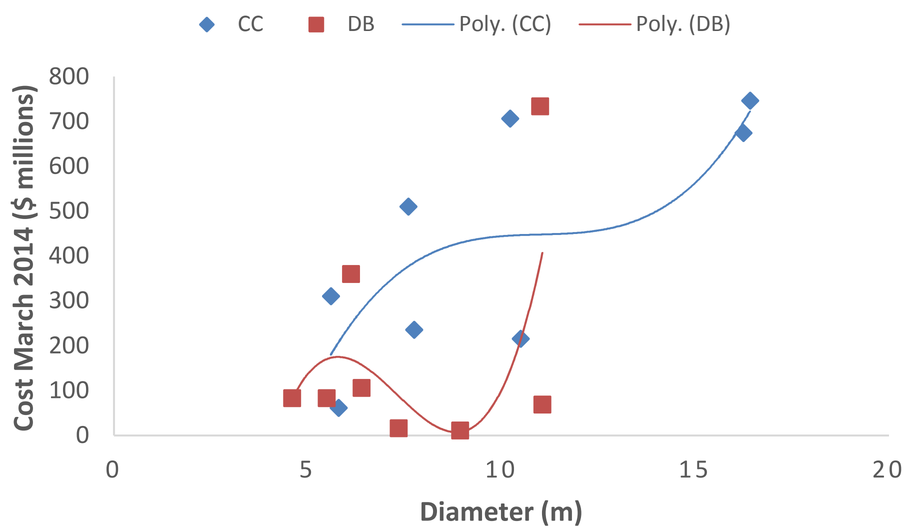

Figure 4.4. Cost against diameter for cut and cover and drill and blast methods

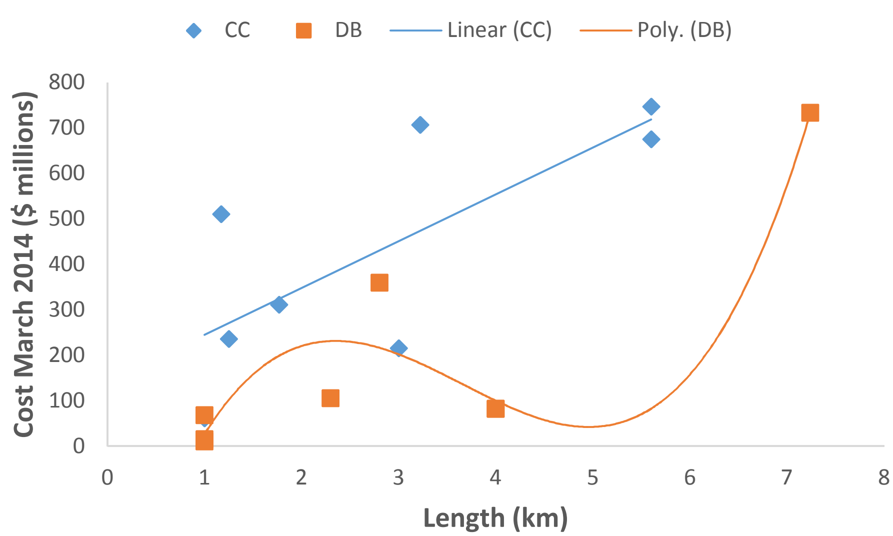

Figure 4.5. Cost against length for cut and cover and drill and blast methods

Table 4.7. Summarized fitted curves for cut and cover and drill and blast excavation methods.

Excavation Method	Data points	R^2	Equation fitted to the curve
Cut and cover	8	0.56	Cost = 102.91L + 141.93
Drill and blast	8	0.91	Cost = $21.362L^3 - 234.17L^2 + 746.82L - 507.42$

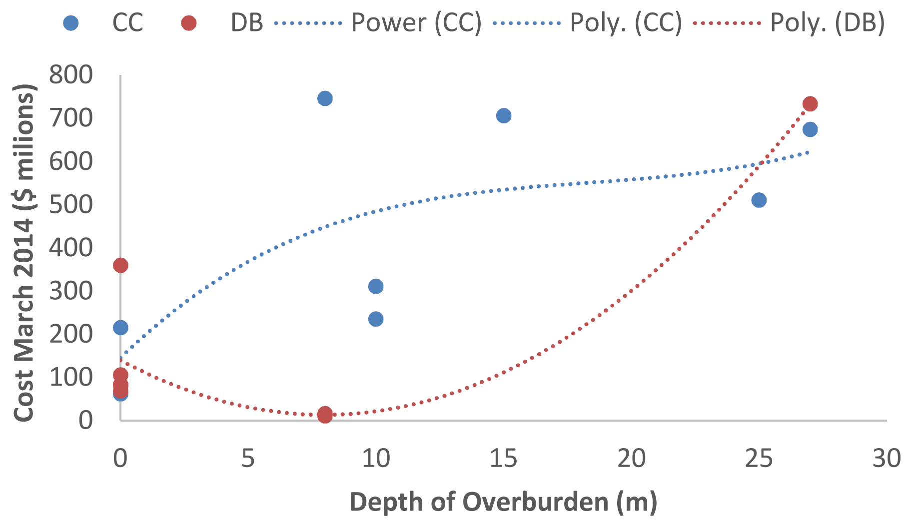

Figure 4.6. Cost against depth of overburden for cut and cover and drill and blast methods

Table 4.8. Summarized fitted curves for cut and cover and drill and blast excavation methods.

Excavation Method	Data points	R^2	Equation fitted to the curve
Cut and cover	8	0.51	Cost = $0.0531De^3 - 2.923De^2 + 57.871De + 145.31$
Drill and blast	8	0.86	Cost = $1.9888De^2 - 31.716De + 139.96$

4.6.1.3. TBM method- railways

In the railway mode of transportation category, the TBM method contained six tunnel projects (Table 4.1). Preliminary data analysis was performed for the following parameters: depth of overburden, tunnel diameter, tunnel length, and the total tunnel cost. The statistical analysis results of the TBM method used in the excavation of tunneling railway projects are presented in Table 4.9 and Figure 4.7.

Table 4.9. Descriptive statistics for depth, length, diameter, and cost in millions dollars.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	32.50	6.86	20.00	36.00	38.00	-1.58	1.93
Length (km)	8.81	6.36	1.87	8.54	19.50	0.84	0.78
Diameter (m)	7.170	1.360	5.700	6.630	9.500	1.13	0.91
Cost($millions)	1472	2266	58	607	6014	2.26	5.24

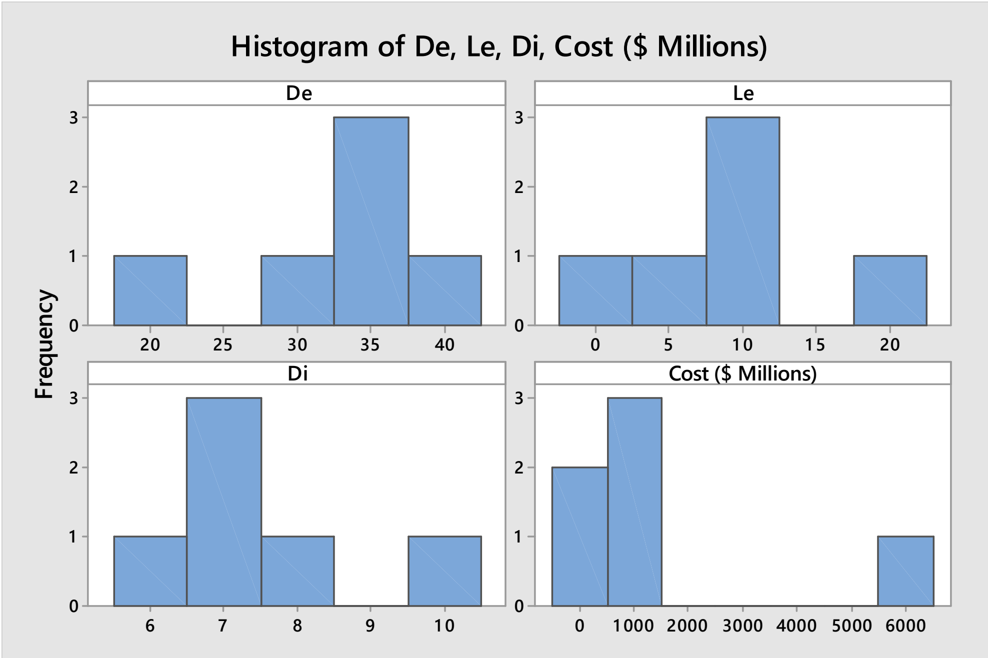

Figure 4.7. Histogram of depth, length, diameter and cost

4.6.1.4. Mixed methods -railways

For the mixed tunnel excavation methods used in railway tunneling projects, this group contained nine tunnel projects. In the analyses, parameters such as depth of overburden, tunnel diameter, tunnel length, and the total tunnel cost were analyzed. The statistical analysis results of the parameters for the mixed tunnel excavation methods are presented in Table 4.10 and Figure 4.8.

Table 4.10. Descriptive statistics for depth, length, diameter, and cost in millions dollars.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	15.11	7.11	0.00	16.00	25.00	-1.05	2.04
Length (km)	5.83	4.11	2.07	5.60	13.50	0.83	-0.34
Diameter (m)	6.573	0.659	5.880	6.400	8.150	1.95	4.65
Cost($millions)	371	355	98	209	1072	1.49	0.84

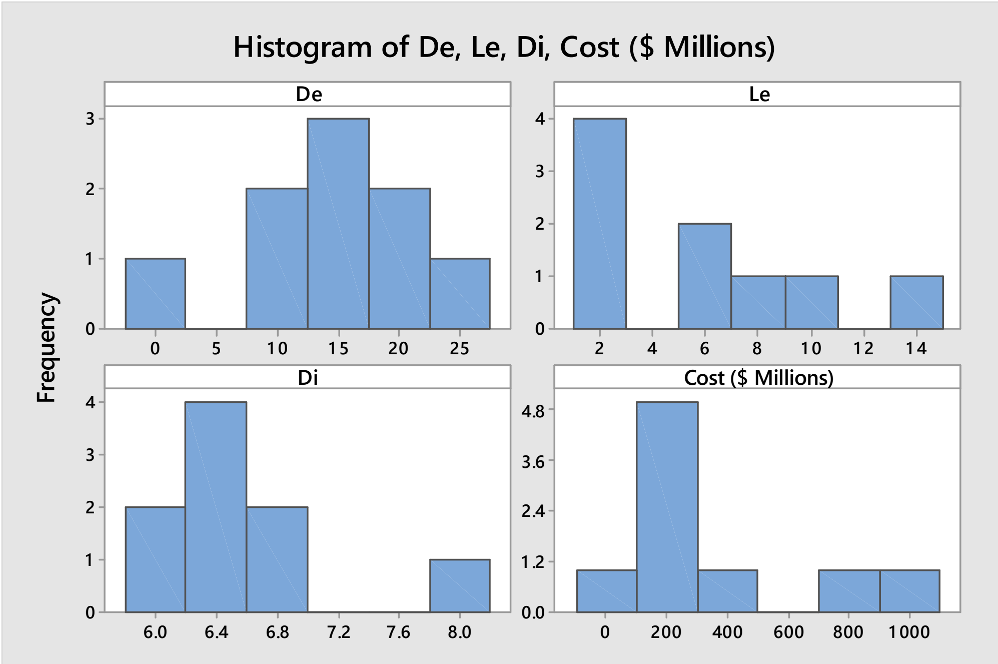

Figure 4.8. Histogram of depth, length, diameter and cost

Plots of the dependent variable (tunnel cost) against the independent variables (diameter, length, and depth) including the regression lines for the two tunnel excavation methods for the railway mode of transportation are presented in Figures 4.9 to 4.11. The figures show plots of cost against diameter, length, and depth including regression lines for cut and cover and drill and blast for railway tunnel projects. Tables 4.11 to 4.13 present the summaries of the fitted equations for the two tunnel excavation methods for railway tunnel projects.

Table 4.11. Summarized fitted curves for mixed and TBM excavation methods.

Excavation Method	Data points	R^2	Equation fitted to the curve
Mixed methods	8	0.22	Cost = $-4991.2D^3 + 94032D^2 - 589426D + 1E+06$
TBM	5	0.96	Cost = $116.95D^2 - 2078.7D + 9282.2$

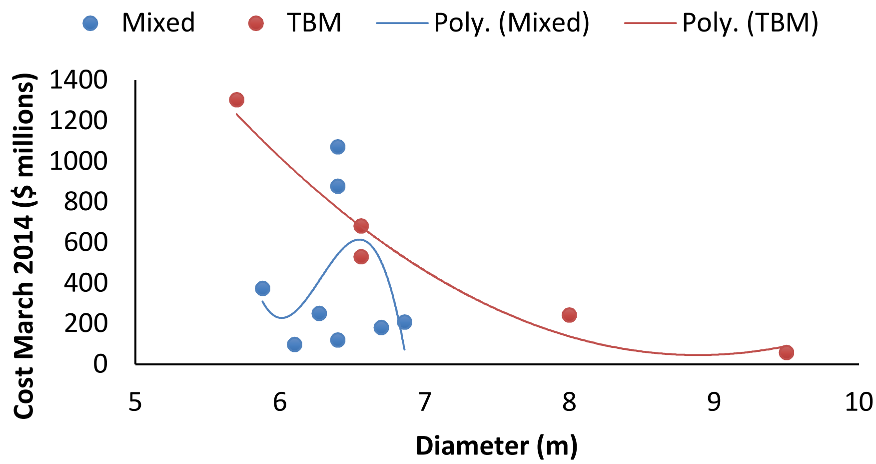

Figure 4.9. Cost against diameter for mixed and TBM methods

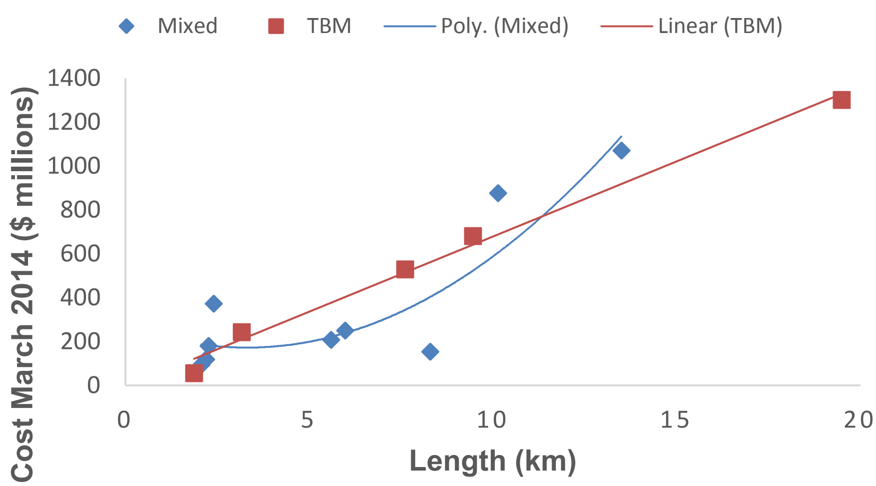

Figure 4.10. Cost against length for mixed and TBM methods

Table 4.12. Summarized fitted curves for mixed and TBM excavation methods.

Excavation Method	Data points	R^2	Equation fitted to the curve
Mixed methods	9	0.81	Cost = $9.2677L^2 - 61.387L + 274.57$
TBM	5	0.99	Cost = $68.431L - 5.8436$

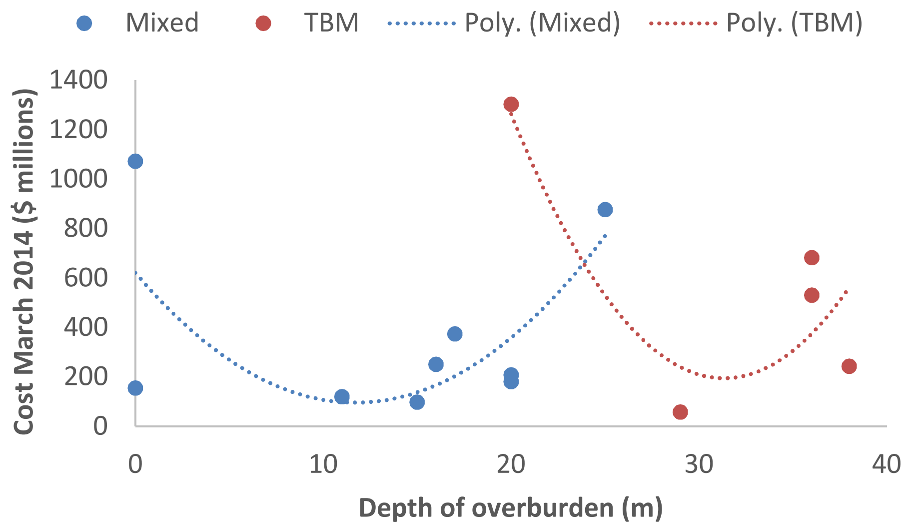

Figure 4.11. Cost against depth of overburden for mixed and TBM methods

Table 4.13. Summarized fitted curves for mixed and TBM excavation methods.

Excavation Method	Data points	R^2	Equation fitted to the curve
Mixed methods	9	0.48	$Cost = 3.8249De^2 - 89.645De + 621.85$
TBM	5	0.72	$Cost = 8.3053De^2 - 520.61De + 8353.9$

4.6.1.5. Mixed methods – metro

The mixed tunnel excavation methods used to excavate metro mode of transportation tunneling projects dataset contained 10 tunnel projects. The remaining other excavation methods were not considered because they had less than six tunnel projects in in the different modes of transportation. In the analyses, the following parameters such as depth of overburden, tunnel diameter, tunnel length, and the total tunnel cost were analyzed. The results of the analyses of the parameters for the mixed tunnel excavation methods are depicted in Figure 4.12 and Table 4.14.

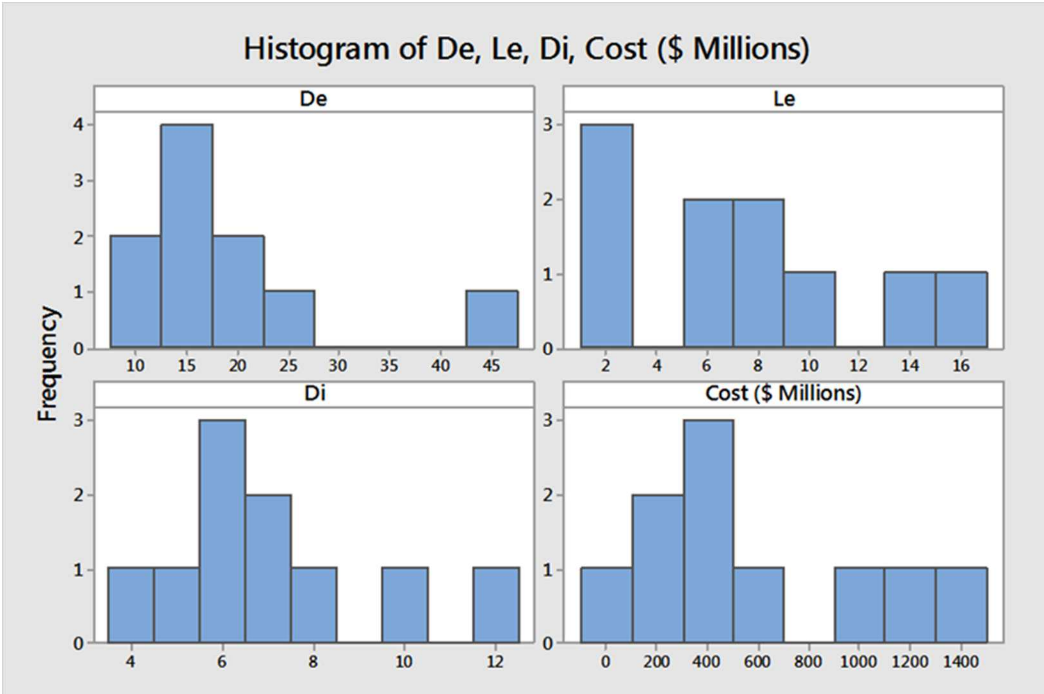

Figure 4.12. Histogram of depth, length, diameter and cost

Table 4.14. Descriptive statistics for depth, length, diameter, and cost in millions dollars.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	18.40	10.57	8.00	15.00	46.00	2.29	6.06
Length (km)	7.39	5.19	1.00	6.85	16.90	0.52	-0.40
Diameter (m)	6.969	2.358	3.800	6.405	11.700	0.95	0.65
Cost($millions)	566	447	88	454	1301	0.62	-1.18

Plots of the dependent variable (tunnel costs) against the independent variables (diameter, length, and depth) including the regression lines for the mixed tunnel excavation methods for the metro transportation tunnel system are depicted in Figures 4.13 to 4.15. Figures 4.13 to 4.15 show the plots of cost against tunnel diameter, length, and depth of overburden including regression lines for mixed tunnel excavation methods for metro tunneling projects. The equations for mixed tunnel excavation methods for metro tunnel projects category are given in Table 4.15.

Table 4.15. Summarized fitted curves for mixed tunnel excavation methods.

Excavation Method	Data points	R^2	Equation fitted to the curve
Mixed methods	10	0.29	Cost = $17.192D^3 - 370.41D^2 + 2455.5D - 4474.8$
Mixed methods	10	0.21	Cost = $-0.6359L^3 + 21.145L^2 - 160.38L + 715.7$
Mixed methods	10	0.70	Cost = $-3.6265De^3 + 169.2De^2 - 2402.4De + 10750$

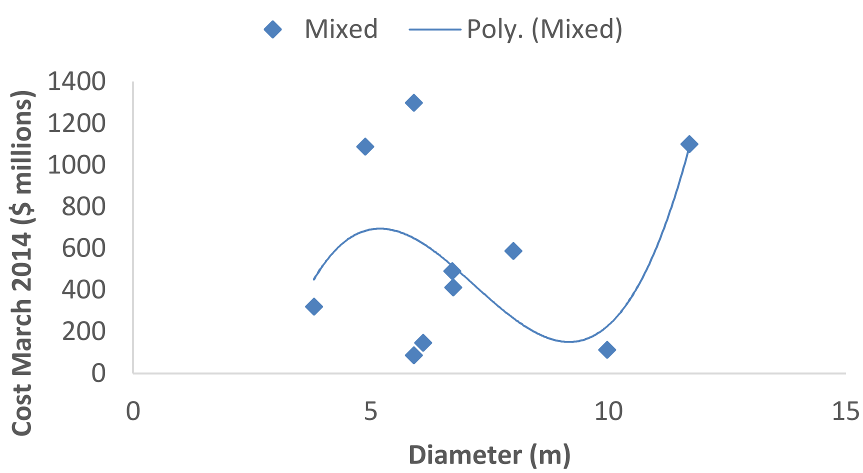

Figure 4.13. Cost against diameter for mixed tunnel excavation methods

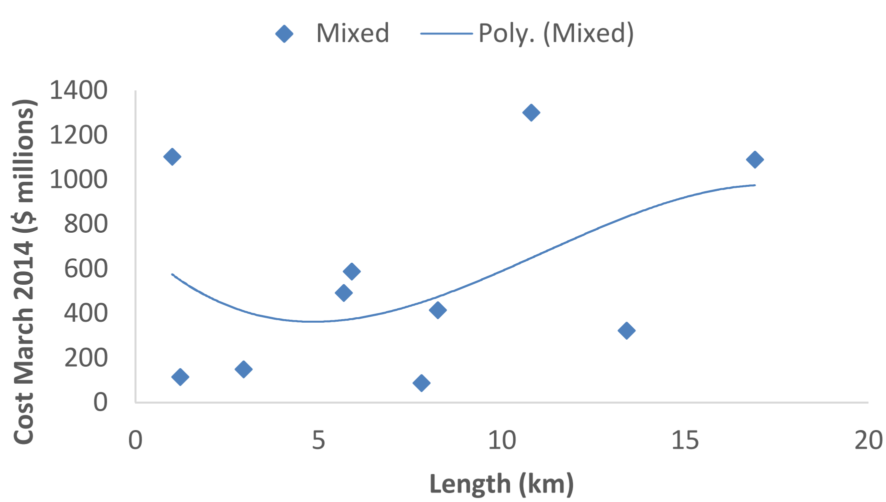

Figure 4.14. Cost against length for mixed tunnel excavation methods

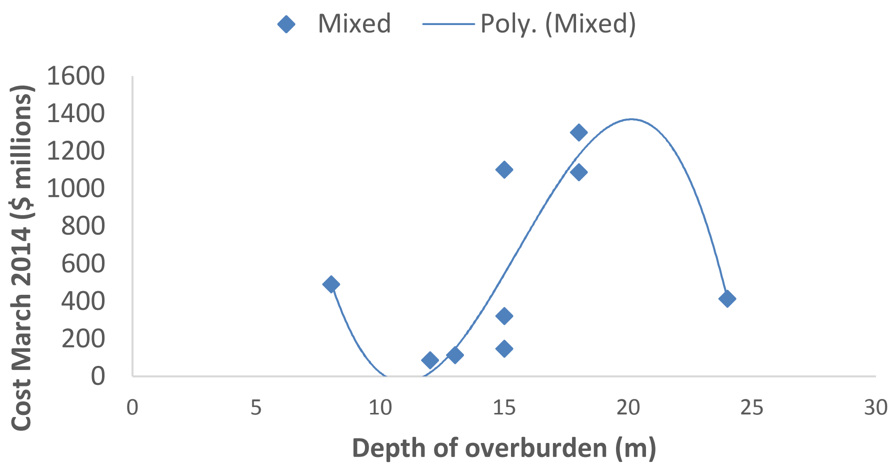

Figure 4.15. Cost against depth of overburden for mixed tunnel excavation methods

4.6.1.6. TBM method- subway

The TBM method data used in the subway tunneling projects had seven points. Preliminary data analysis was performed for the following parameters: depth of overburden, tunnel diameter, tunnel length, and the total tunnel cost. The results of the statistical analysis for the TBM for metro transportation system are given in Figure 4.16 and Table 4.16.

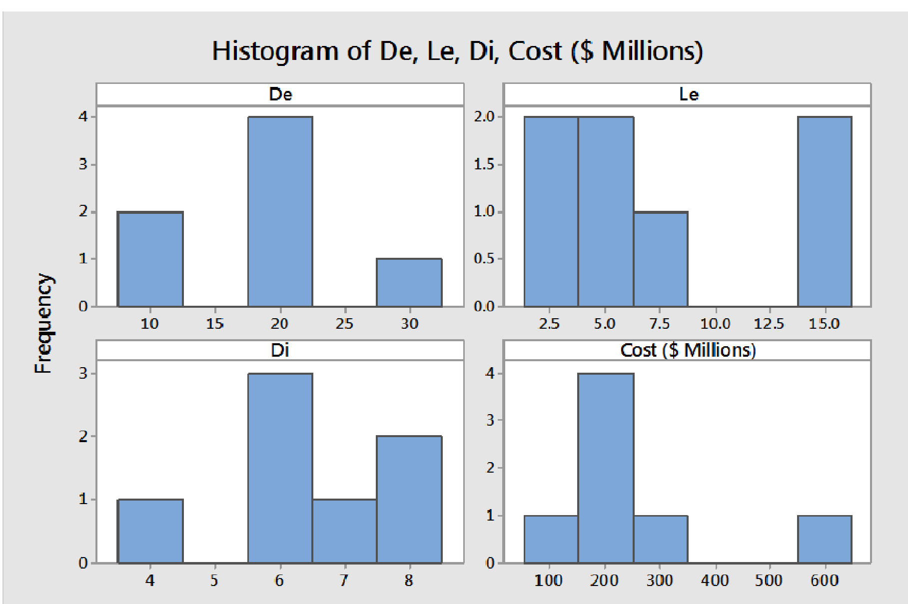

Figure 4.16. Histogram of depth, length, diameter and cost

Table 4.16. Descriptive statistics for depth, length, diameter, and cost in millions dollars.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	18.57	7.07	8.00	20.00	30.00	0.04	0.49
Length (km)	7.34	5.36	1.93	6.00	15.65	0.91	-0.87
Diameter (m)	6.370	1.541	3.800	5.910	8.230	-0.30	0.15
Cost($millions)	258.8	181.3	86.0	212.1	645.2	2.00	4.68

4.6.1.7. Mixed methods- subway

Mixed tunnel excavation methods used for the subway mode of transportation tunneling projects dataset contained 17 tunnel projects. The following parameters: depth of overburden, tunnel diameter, tunnel length, and the total tunnel cost examined. The exploratory data analysis results for the parameters for the mixed tunnel excavation methods are presented in Figure 4.17 and Table 4.17.

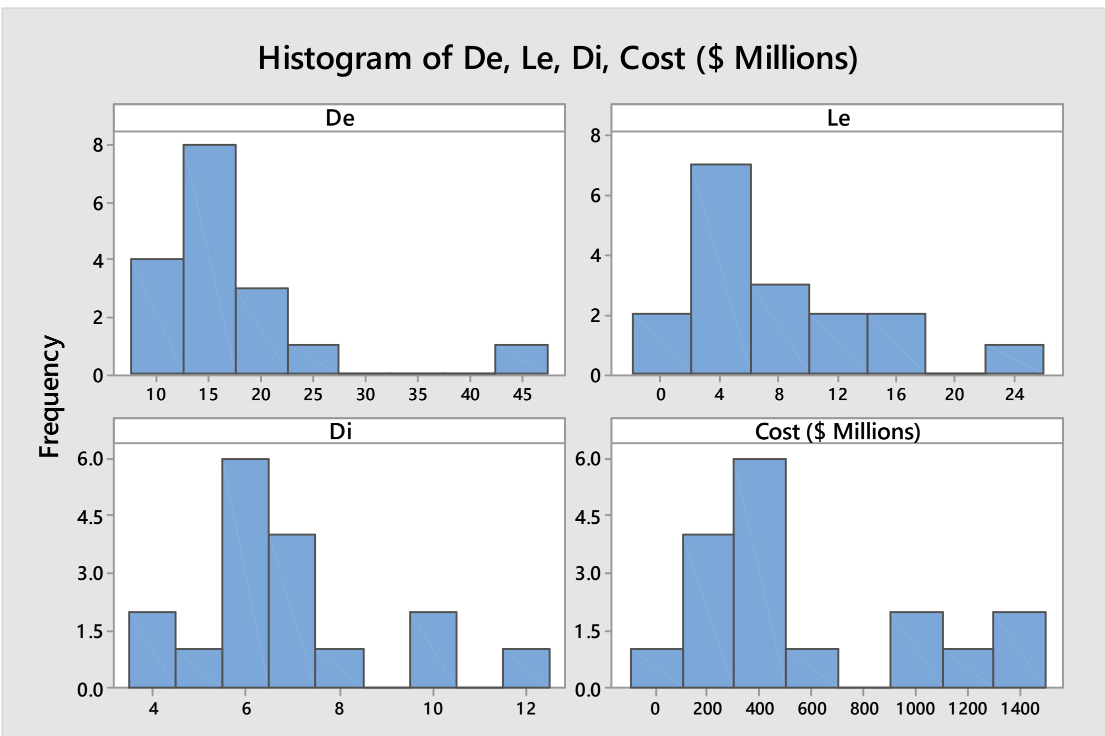

Figure 4.17. Histogram of depth, length, diameter and cost

Table 4.17. Descriptive statistics for depth, length, diameter, and cost in millions dollars.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	16.65	8.38	8.00	15.00	46.00	2.94	10.26
Length (km)	8.25	6.41	1.00	5.90	24.00	1.16	0.84
Diameter (m)	6.832	2.096	3.800	6.300	11.700	0.99	0.77
Cost($millions)	573	440	88	415	1475	0.89	-0.53

Plots of the dependent variable (tunnel costs) against the independent variables (diameter, length, and depth) including the regression lines for the two tunnel excavation methods for the subway transportation tunnel mode are presented. Figures 4.18 to 4.20 show the plots of cost against tunnel diameter, length, and depth of overburden including regression lines for mixed and TBM tunnel excavation methods for subway tunnel projects. Table 4.18 presents the summary of the fitted equations for the tunnel excavation methods for the three independent variables of subway tunnel projects.

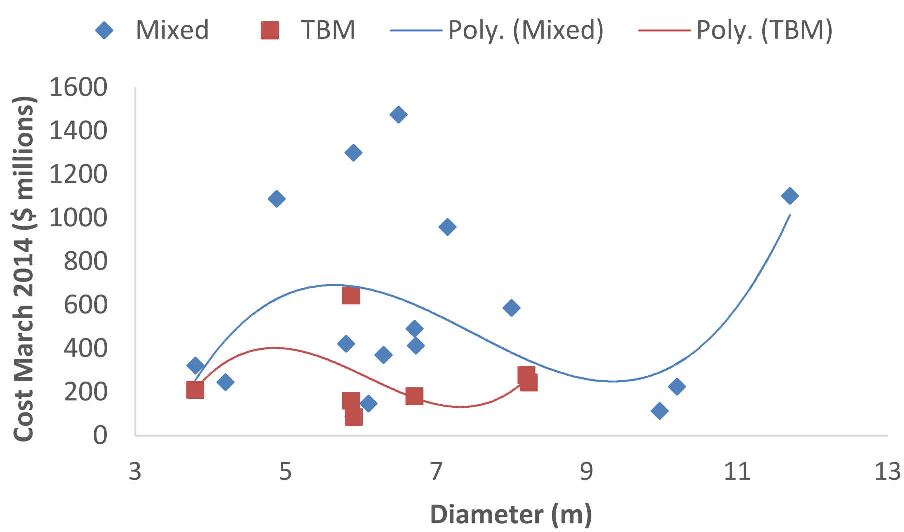

Figure 4.18. Cost against diameter for mixed and TBM tunnel excavation methods

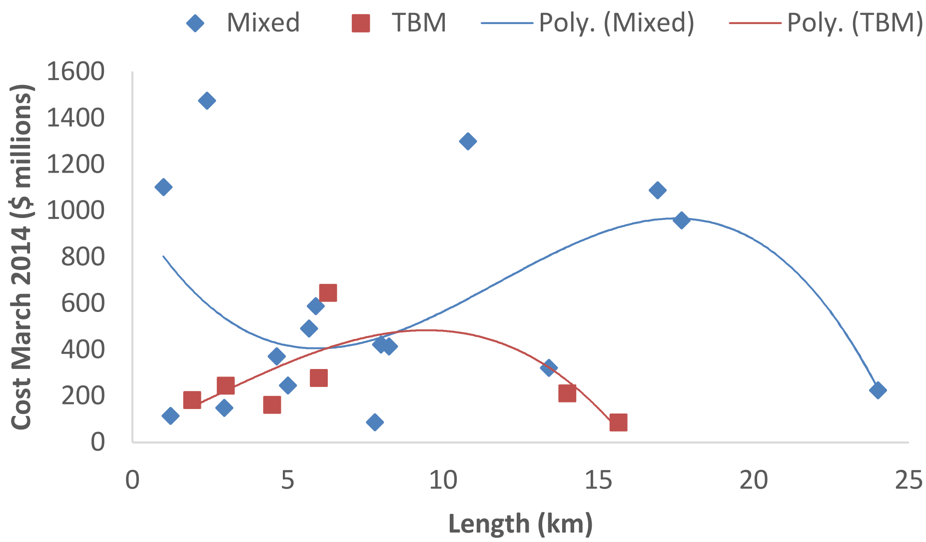

Figure 4.19. Cost against length for mixed and TBM tunnel excavation methods

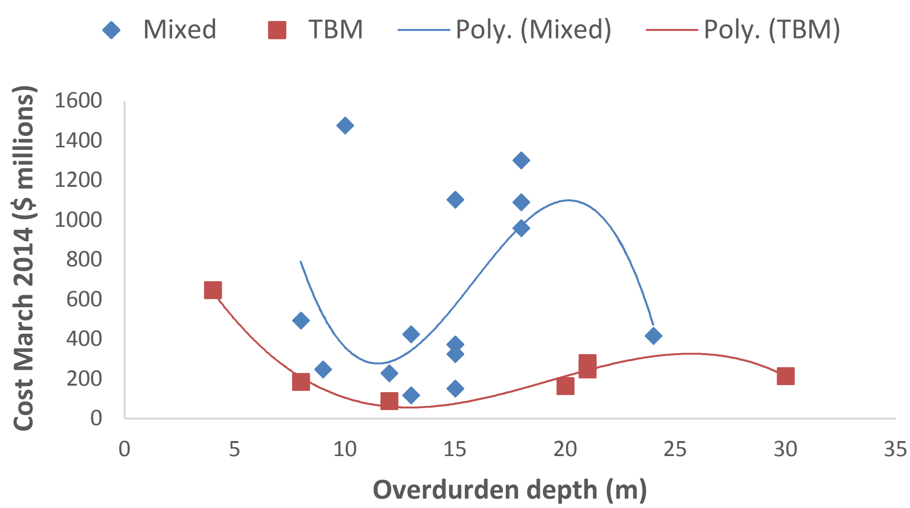

Figure 4.20. Cost against depth of overburden for mixed and TBM excavation methods

Table 4.18. Summarized fitted curves for mixed and TBM excavation methods.

Excavation Method	Data points	R^2	Equation fitted to the curve
Mixed methods	15	0.18	Cost = $17.435D^3 - 391.97D^2 + 2758D - 5523.1$
TBM	6	0.07	Cost = $35.889D^3 - 655.63D^2 + 3828D - 6835.5$
Mixed methods	16	0.24	Cost = $-0.7289L^3 + 25.627L^2 - 227.46L + 1005.4$
TMB	7	0.50	Cost = $-0.4017L^3 + 2.5799L^2 + 59.317L + 32.236$
Mixed methods	14	0.28	Cost = $-2.533\mathrm{De}^3 + 120.32\mathrm{De}^2 - 1762.5\mathrm{De} + 8485.6$
TBM	6	0.97	Cost = $-0.261\mathrm{De}^3 + 15.108\mathrm{De}^2 - 260.01\mathrm{De} + 1453.5$

4.6.2. Type of Geology

The subsurface geology was examined in two ways: namely (1) the entire dataset and data subsets on the basis of the transportation modes. In the scenarios considered, the datasets were categorized as hard and soft rock. In the analyses of type of geology, parameters such as depth of overburden, tunnel diameter, tunnel length, and the total tunnel cost were investigated. The results of statistical analysis of the transportation data based on type of geology are presented as follows.

The entire dataset was divided into hard and soft rock; each group had 38 and 41 projects respectively. In terms of percentage distribution, hard rock had 48% and soft rock had 52% for the projects under type of geology.

Hard rock dataset had 38 tunnel projects constructed between 1997 and 2014. The parameters analyzed were depth of overburden, diameter, length, and the total tunnel cost. Diagrammatic representations of the parameters in the form of histograms are presented in Figure 4.21. The descriptive statistics for depth of overburden, diameter, length of tunnel, and total tunnel cost are shown in Table 4.19. The deepest depth of overburden in the dataset was 38.00 m with a mean and a standard deviation of 15.06 m and 12.50 m respectively. The median value of the depth of overburden was 14.00 m, which shows a deviation from the mean value of 15.06 m. For the diameter variable, the average tunnel diameter was 7.580 m with a standard deviation of 2.932 m. The median was 6.930 m compared with a mean of 7.580 m, an indication of the dataset being left-skewed. For length and total cost, the mean was 4.358 m, and $264.2 million and standard deviations of 5.162 m and $218.7 million respectively. Other pertinent statistics for depth of overburden, length, diameter, and cost are presented in Figure 4.21 and Table 4.19.

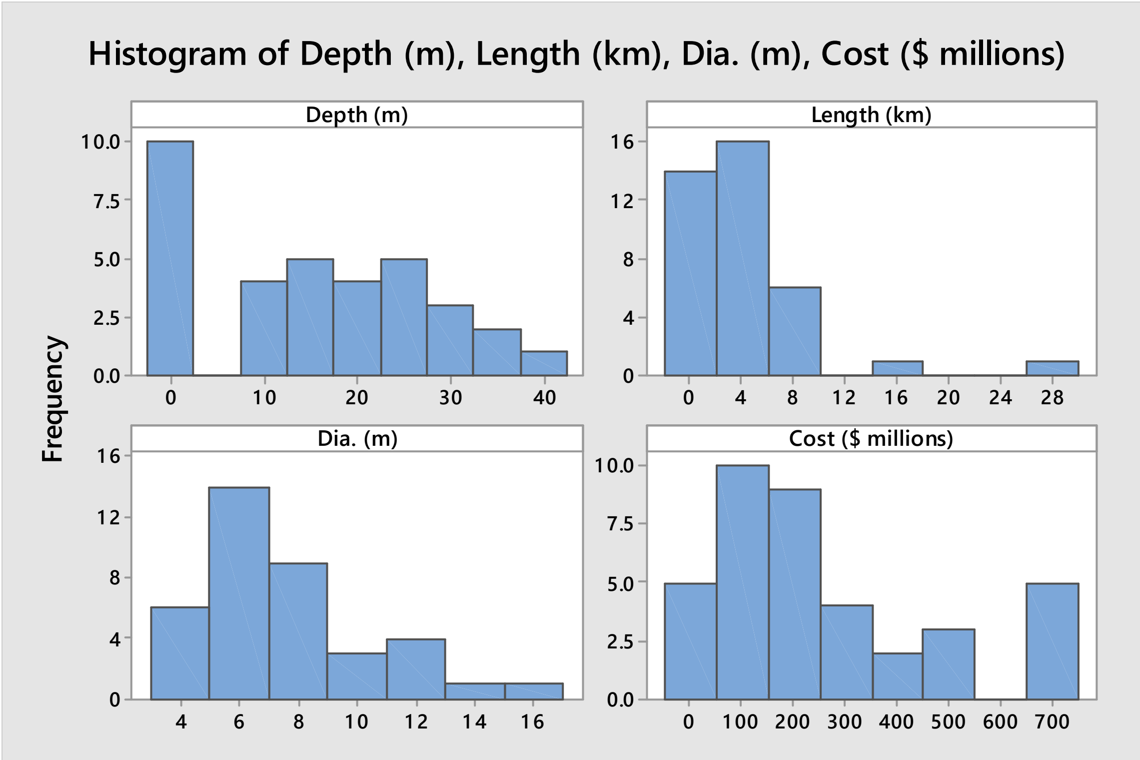

Figure 4.21. Histogram of depth, length, diameter and cost

Table 4.19. Descriptive statistics for depth, length, diameter, and cost in millions dollars.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	15.06	12.50	0.00	14.00	38.00	0.20	-1.21
Length (m)	4.358	5.162	1.000	2.652	29.100	3.31	14.07
Diameter (m)	7.580	2.932	3.250	6.930	16.250	0.95	0.80
Cost($millions)	264.2	218.7	11.2	213.8	733.5	0.92	-0.26

Plots of the dependent variable (tunnel costs) against the independent variables (diameter, length, and depth) including the regression lines for the hard rock for all the transportation tunneling projects are presented. Table 4.20 presents the summary of the fitted equations for the three variables of the hard rock dataset for the transportation tunneling projects. The following Figures 4.22, 4.23, and 4.24 show the plots of cost against tunnel diameter, length, and depth of overburden including regression lines for hard rock dataset.

Table 4.20. Summarized fitted curves for the hard rock dataset.

Geology	Data points	R^2	Equation fitted to the curve
Hard rock	38	0.21	Cost = $0.9561D^3 - 26.876D^2 + 260.52D - 562.34$
Hard rock	38	0.21	Cost = $91.142L^{0.6638}$
Hard rock	38	0.13	Cost = $-0.0429De^3 + 1.9096De^2 - 19.274De + 238.75$

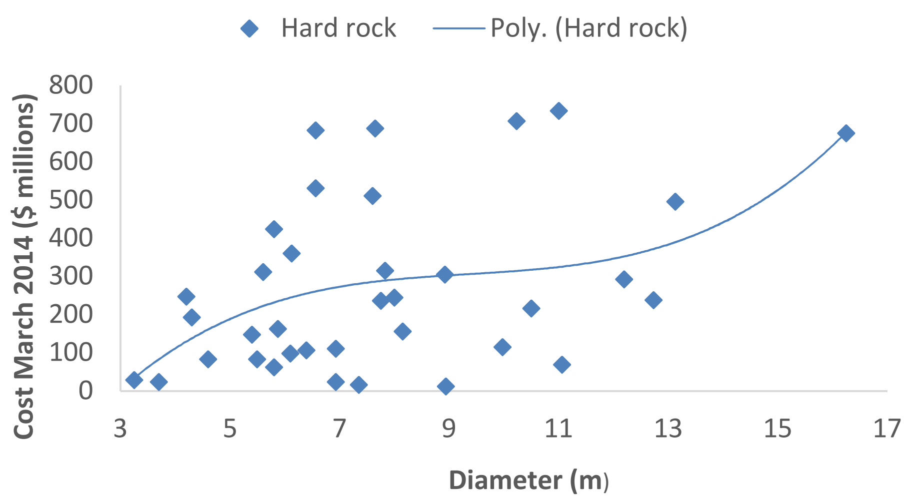

Figure 4.22. Cost against diameter for the hard rock dataset

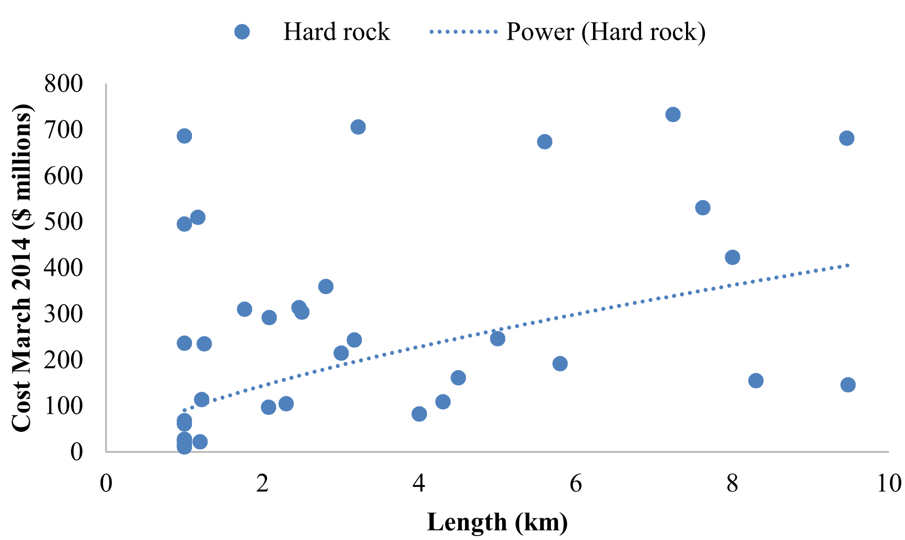

Figure 4.23. Cost against length of tunnel for the hard rock dataset

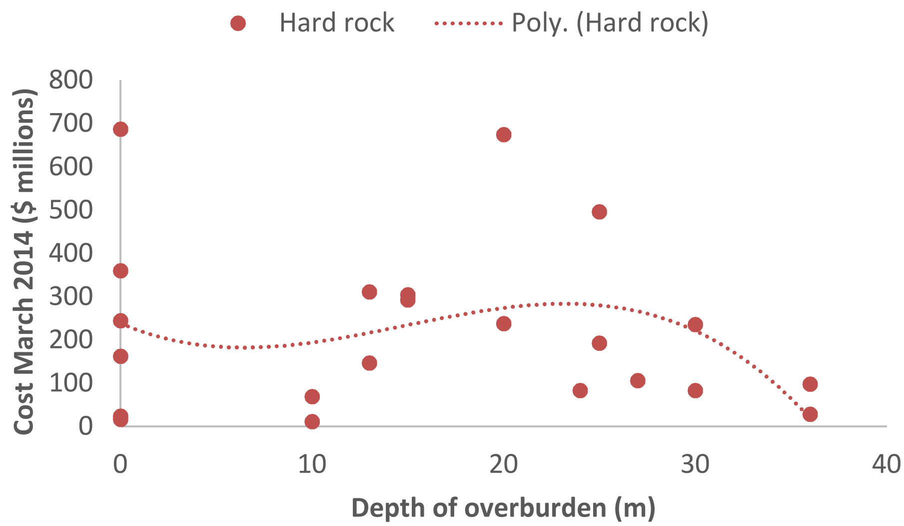

Figure 4.24. Cost against depth of overburden for the hard rock dataset

The soft rock dataset had 41 tunnel projects constructed between 1998 and 2014. The parameters analyzed were depth of overburden, diameter, length, and the total tunnel cost. Diagrammatic representations of the parameters in the form of histograms are shown in Figure 4.25. The descriptive statistics for depth of overburden, diameter, length of tunnel, and total tunnel cost are shown in Table 4.21. The deepest depth of overburden was 57.00 m with an average and a standard deviation of 15.06 m, and 12.50 m respectively. The median was 14.00 m which shows a deviation from the mean of 15.06 m. In the case of diameter dataset, the average tunnel diameter was 7.580 m with a standard deviation of 2.932 m. The median was 6.930 m compared with a mean of 7.580 m, an indication of the dataset being left-skewed. For length and total cost, the average mean was 4.358 m, and $264.2 million and standard deviations of 5.162 m and $218.7 million respectively. Other pertinent statistics for depth of overburden, length, diameter, and cost are presented in Figure 4.25 and Table 4.21.

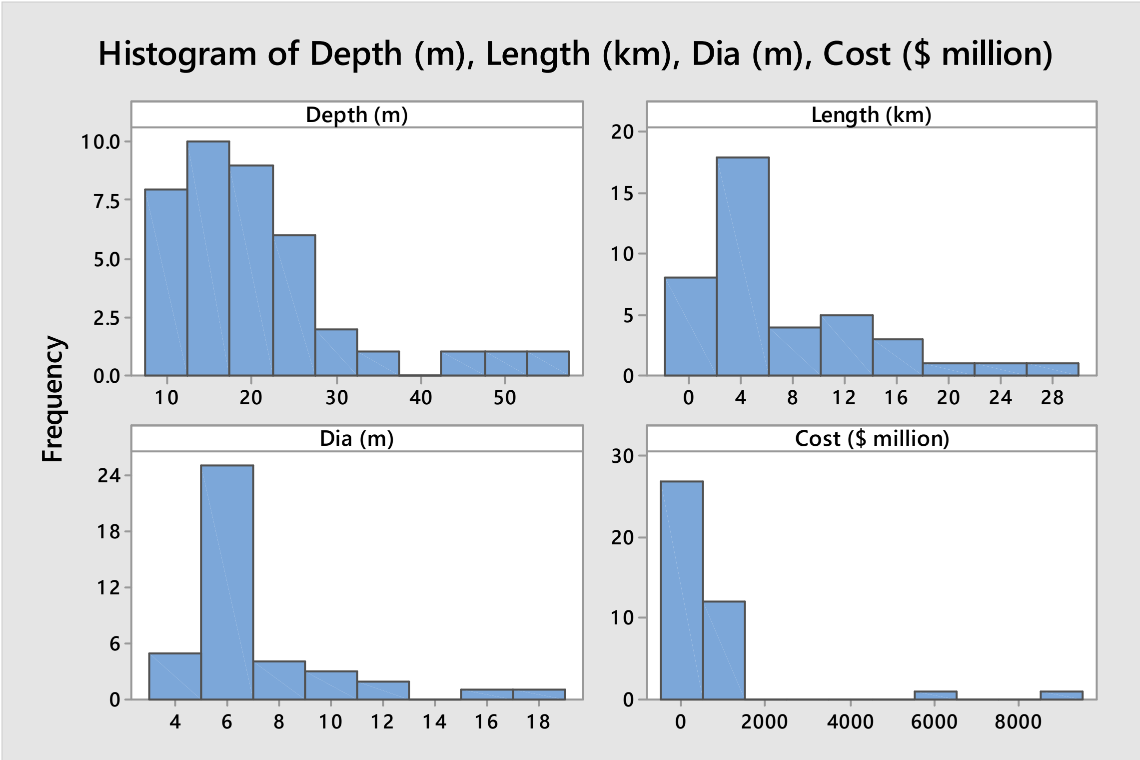

Figure 4.25. Histogram of depth, length, diameter and cost

Table 4.21. Descriptive statistics for depth, length, diameter, and cost in millions dollars.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	20.79	11.01	8.00	18.00	57.00	1.71	3.14
Length (m)	7.11	6.64	1.00	5.20	28.00	1.50	1.83
Diameter (m)	7.276	2.774	3.800	6.400	17.200	1.99	4.45
Cost($millions)	808	1633	34	372	9090	4.25	19.01

Plots of the dependent variable (tunnel costs) against the independent variables (diameter, length, and depth) including the regression lines for soft rock for transportation tunneling projects are presented. Table 4.22 presents the summary of the fitted equations for the soft rock category of the transportation tunneling projects. Figures 4.26 to 4.28 show the plots of cost against diameter, length, and depth of overburden together with regression lines for soft rock dataset.

Table 4.22. Summarized fitted curves for the soft rock dataset.

Geology	Data points	R^2	Equation fitted to the curve
Soft rock	40	0.26	Cost = $3.8754D^3 - 85.666D^2 + 580.53D - 731.29$
Soft rock	39	0.55	Cost = $1.5769L^3 - 52.029L^2 + 507L - 585.44$
Soft rock	37	0.03	Cost = $0.1821De^3 - 11.649De^2 + 230.92De - 941.73$

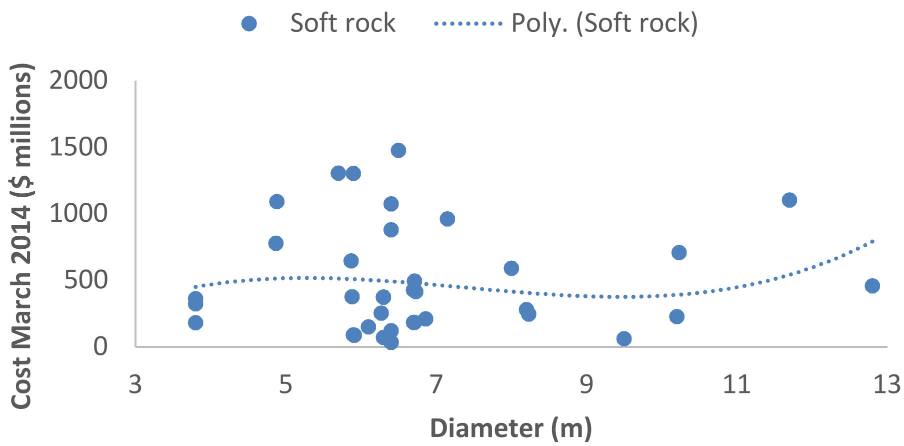

Figure 4.26. Cost against diameter of tunnel for the soft rock dataset

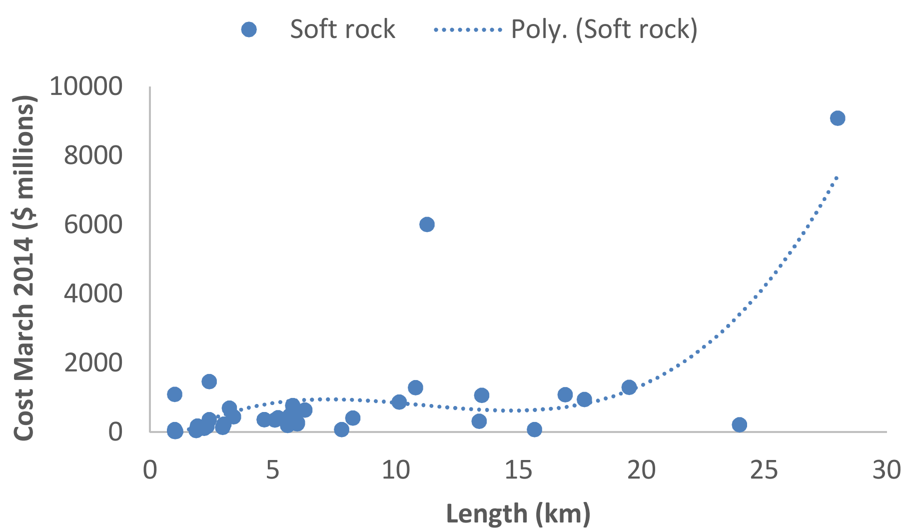

Figure 4.27. Cost against length of tunnel for the soft rock dataset

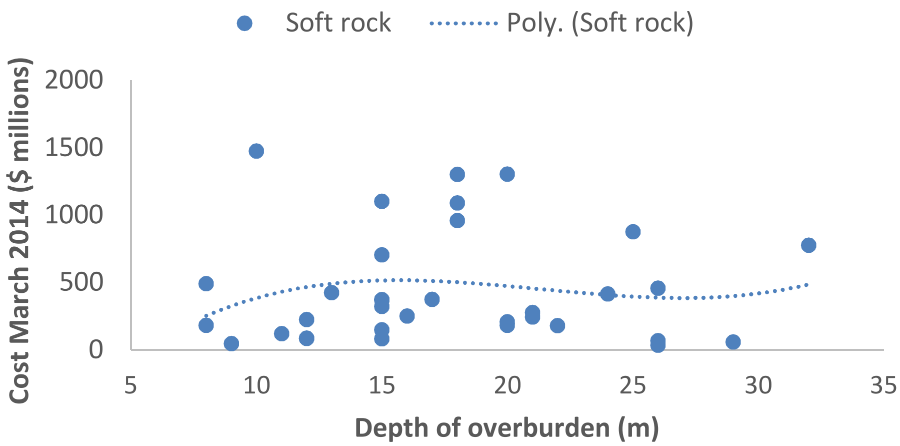

Figure 4.28. Cost against overburden depth of tunnel for the soft rock dataset

Two transportation tunnel projects with higher costs ($9,090 million and $6,014 million) compared to a mean of $808 million could be considered outliers. The two tunnel projects were excluded from the analyses. Three other tunnel projects with higher depth of overburden (57 m, 46 m, and 50 m for the soft rock dataset (SD 11.01 m) compared to the average depth of 20.79 m could be considered outliers.

4.6.2.1. Geology-Modes of transportation

In this section, the type of geology for the different transportation modes is analyzed. The geology data for the transportation modes were divided into hard and soft rock as summarized in Table 4.23.

Table 4.23. Summarized results for type of geology for the transportation modes.

	Geology-hard rock	Geology-soft rock
Highways	19	2
Railways	8	11
Subways	4	13
Metro	11	20

4.6.2.2. Geology- highways

The highways dataset for the hard rock group had 19 tunnel projects while the soft rock group had two tunnel projects only. For this category only the hard rock dataset was analyzed as the soft rock group had only two projects. The following parameters were investigated: depth of overburden, tunnel diameter, tunnel length, and the total tunnel cost. The statistical analysis results of the hard rock based on type of geology are presented in Figure 4.29 and Table 4.24.

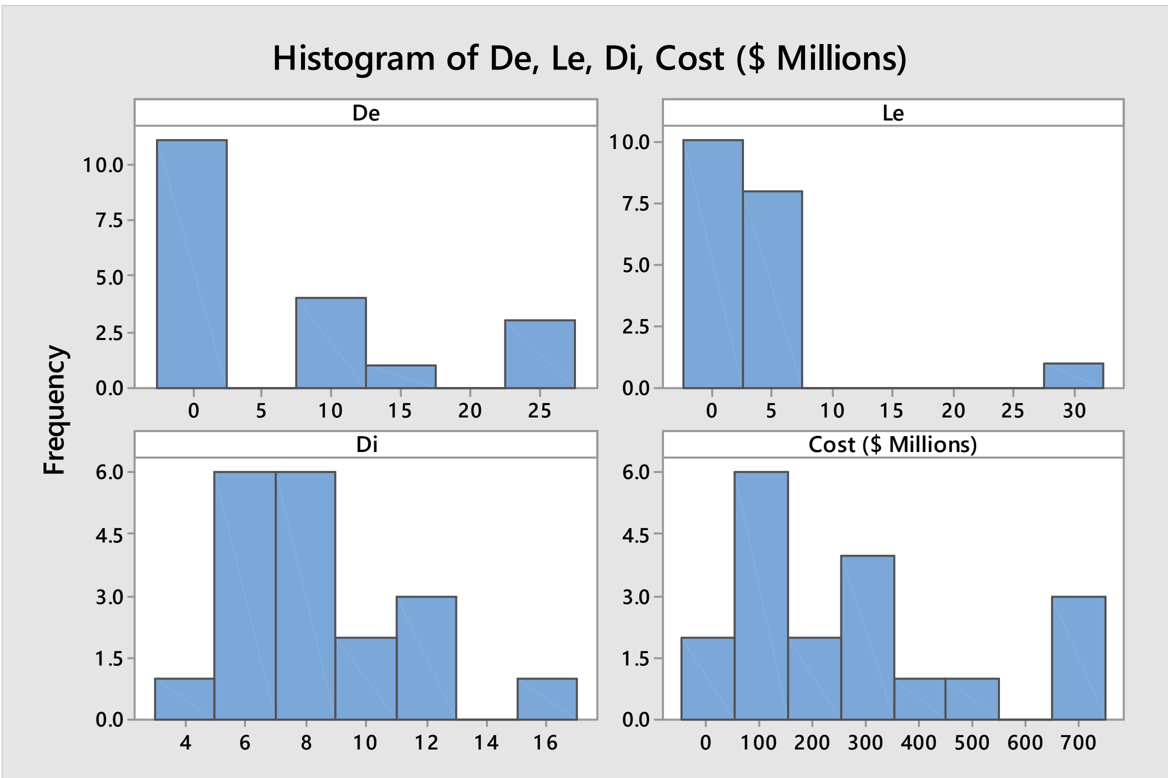

Figure 4.29. Histogram of depth, length, diameter and cost

Table 4.24. Descriptive statistics for depth, length, diameter, and cost in millions dollars.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	6.84	9.85	0.00	0.00	27.00	1.26	0.28
Length (m)	4.02	6.28	1.00	2.46	29.00	3.88	15.94
Diameter (m)	8.368	2.948	4.600	7.750	16.250	1.06	1.25
Cost($millions)	275.0	232.6	11.2	235.7	733.5	0.88	-0.27

Plots of the dependent variable (tunnel costs) against the independent variables (diameter, length, and depth) including the regression lines for hard rock for highway tunneling projects are presented Figures 4.30 to 4.32 show the plots of cost against diameter, length, and depth of overburden together with regression lines for hard rock dataset. Table 4.25 presents the summary of the fitted equations for the hard rock category of the highway tunneling projects.

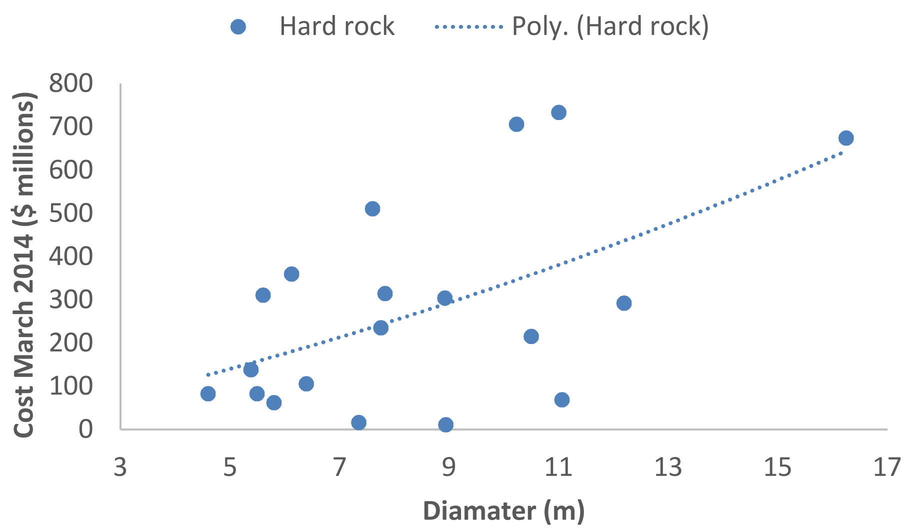

Figure 4.30. Cost against diameter of tunnel for the hard rock dataset

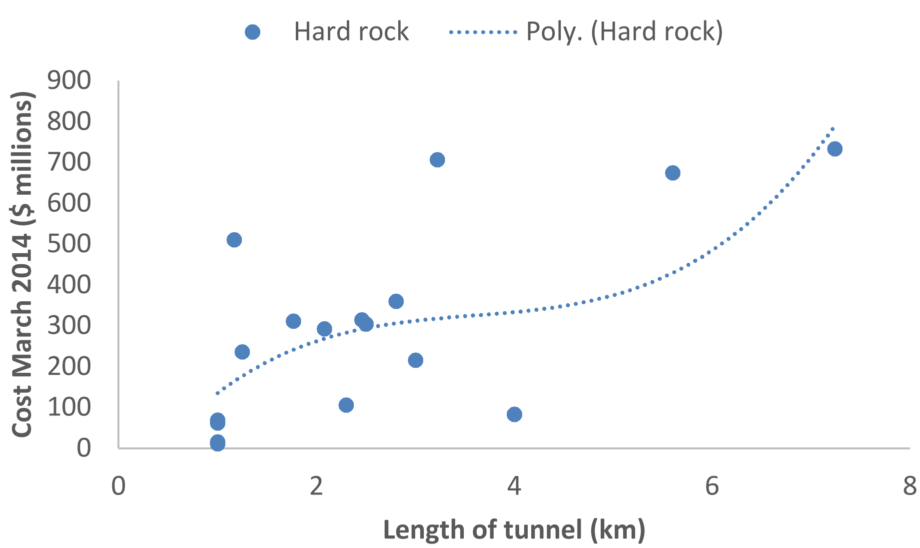

Figure 4.31. Cost against length of tunnel for the hard rock dataset

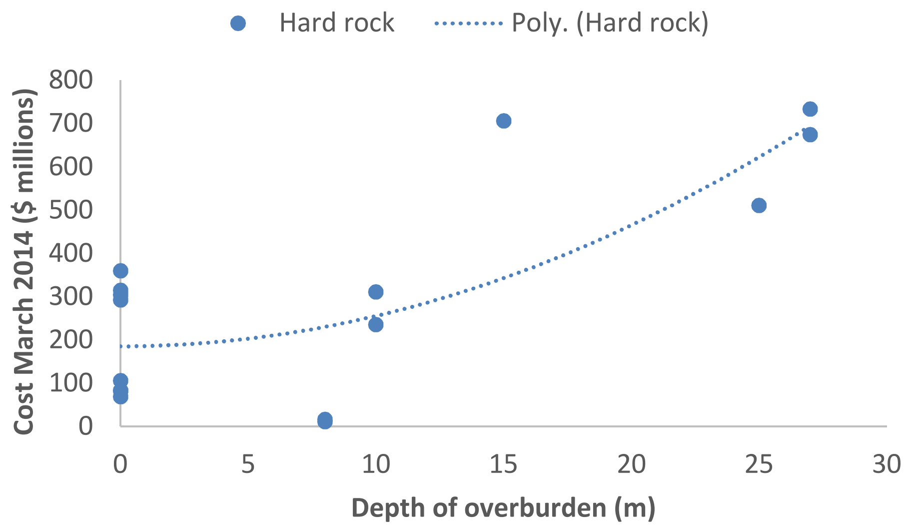

Figure 4.32. Cost against overburden depth of tunnel for the hard rock dataset

Table 4.25. Summarized fitted curves for the hard rock dataset-highways.

Excavation Method	Data points	R^2	Equation fitted to the curve
Hard rock	19	0.30	Cost = $0.9002D^2 + 25.694D - 10.469$
Hard rock	18	0.42	Cost = $8.1277L^3 - 87.478L^2 + 332.82L - 118.21$
Hard rock	19	0.60	Cost = $0.6981De^2 + 0.0481De + 185.17$

4.6.2.3. Geology-railways

For the geology dataset for railway mode of transportation, it contained both hard and soft rock tunneling projects. The dataset contained 8 and 11 tunnel projects for hard and soft rock data, respectively. In the analyses of the railway mode of transportation, parameters such as depth of overburden, tunnel diameter, tunnel length, and the total tunnel cost were analyzed for the two groups of datasets. The exploratory analyses results for the parameters for the hard rock dataset are presented in Figure 4.33 and Table 4.26, while those for the soft rock dataset are depicted in Table 4.27 and Figure 4.34.

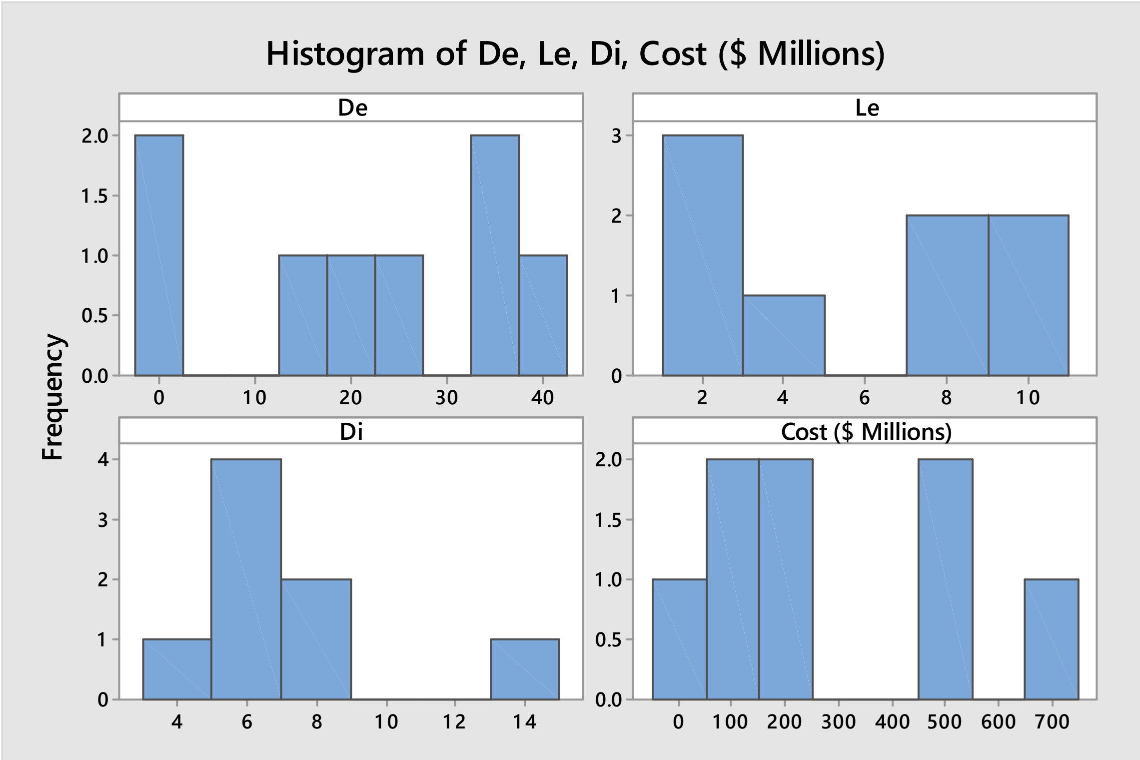

Figure 4.33. Histogram of hard rock data for depth, length, diameter and tunnel cost

Table 4.26. Descriptive statistics of hard rock for depth, length, diameter, and cost.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	21.38	15.45	0.00	23.00	38.00	-0.46	-1.37
Length (km)	5.26	3.80	1.00	5.39	9.48	-0.02	-2.39
Diameter (m)	7.14	2.87	3.25	6.56	13.13	1.21	2.84
Cost($millions)	297.6	239.0	28.3	199.8	682.0	0.60	-1.31

Table 4.27. Descriptive statistics of soft rock for depth, length, diameter, and cost.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	20.45	7.69	9.00	20.00	36.00	0.54	0.56
Length (km)	6.88	5.99	1.00	5.60	19.50	1.02	0.24
Diameter (m)	7.64	3.33	5.70	6.40	17.20	2.85	8.44
Cost($millions)	955	1733.0	48.0	252.0	6014.0	2.96	9.19

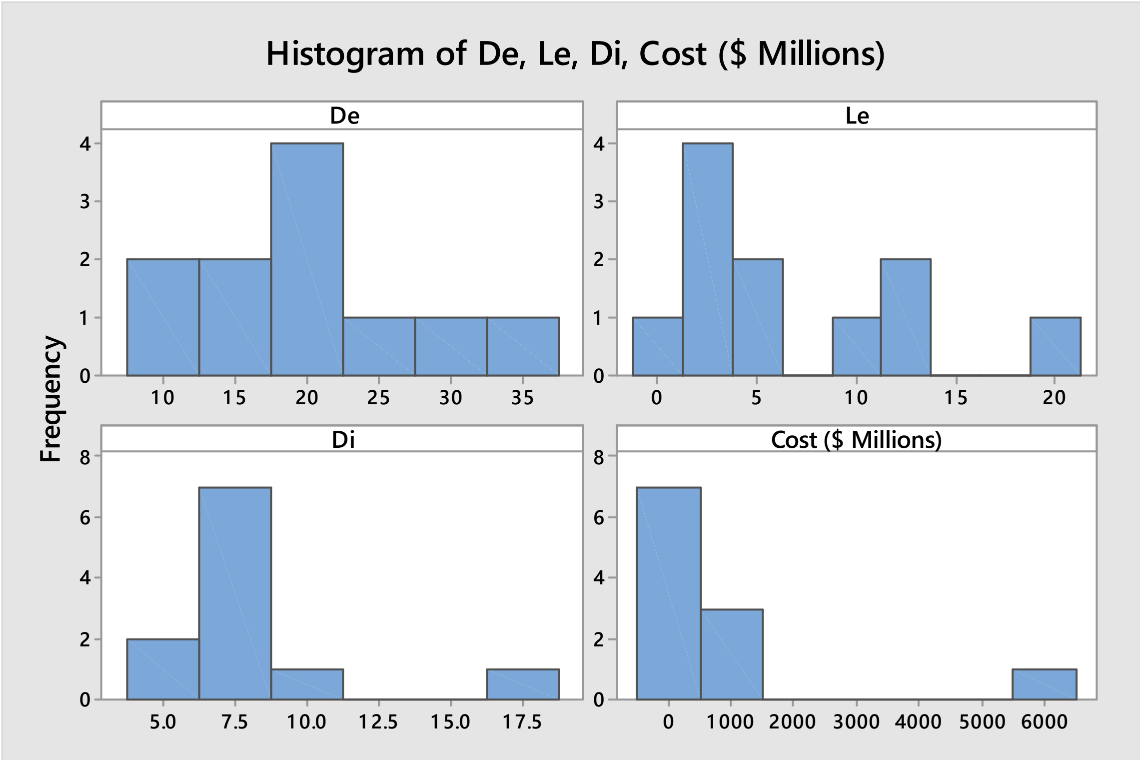

Figure 4.34. Histogram of soft rock data for depth, length, diameter and cost

Plots of the dependent variable (tunnel costs) against the independent variables (diameter, length, and depth) including the regression lines for hard rock for the railway mode of transportation tunneling projects are presented. Table 4.28 presents the summary of the fitted equations for the hard rock category of the railway tunneling projects. Figures 4.35 to 4.37 show the plots of cost against diameter, length, and depth of overburden together with regression lines for the hard rock dataset.

Table 4.28. Summarized fitted curves for the hard rock dataset-highways.

Excavation Method	Data points	R^2	Equation fitted to the curve
Hard rock	8	0.51	Cost = $5.4373D^{1.9041}$
Hard rock	8	0.19	Cost = $109.76L^{0.4634}$
Hard rock	8	0.35	Cost = $0.2605De^2 + 1.0041De + 145.6$

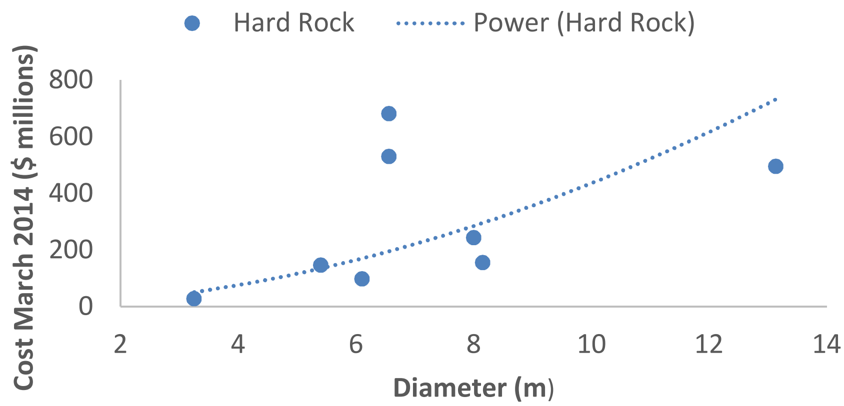

Figure 4.35. Cost against diameter of tunnel for the hard rock dataset

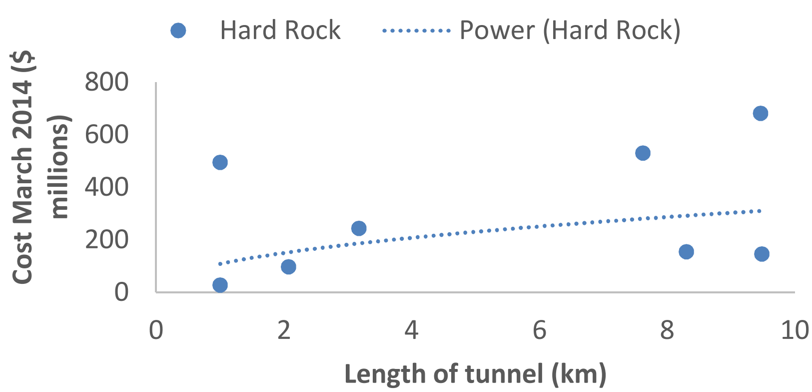

Figure 4.36. Cost against length of tunnel for the hard rock dataset

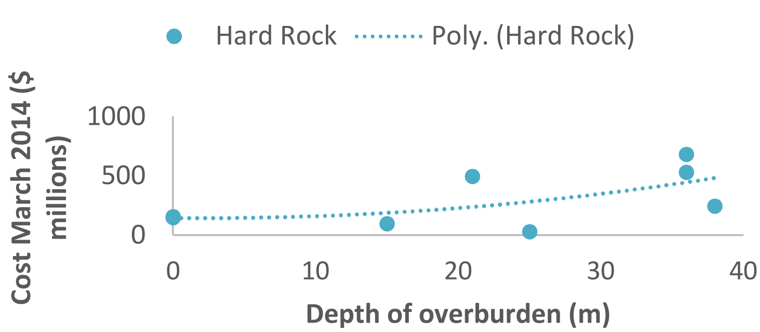

Figure 4.37. Cost against length of tunnel for the hard rock dataset

Plots of the dependent variable (tunnel costs) against the independent variables (diameter, length, and depth) including the regression lines for soft rock for the railway mode of tunneling projects are presented. Figures 4.38 to 4.40 show the plots of cost against diameter, length, and depth of overburden together with regression lines for the soft rock dataset. Table 4.29 presents the summary of the fitted equations for the soft rock category of the railway tunneling projects.

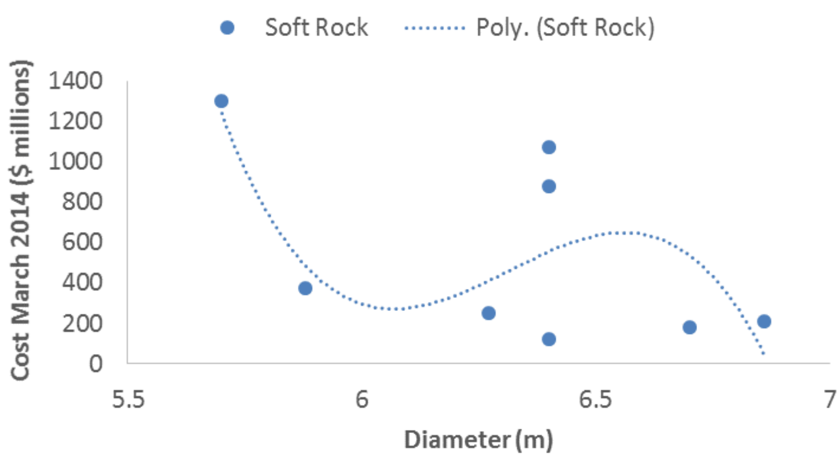

Figure 4.38. Cost against diameter of tunnel for the soft rock dataset

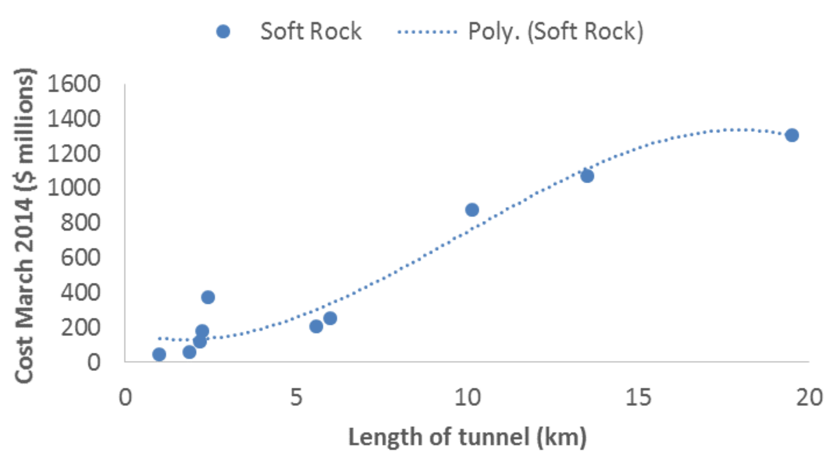

Figure 4.39. Cost against length of tunnel for the soft rock dataset

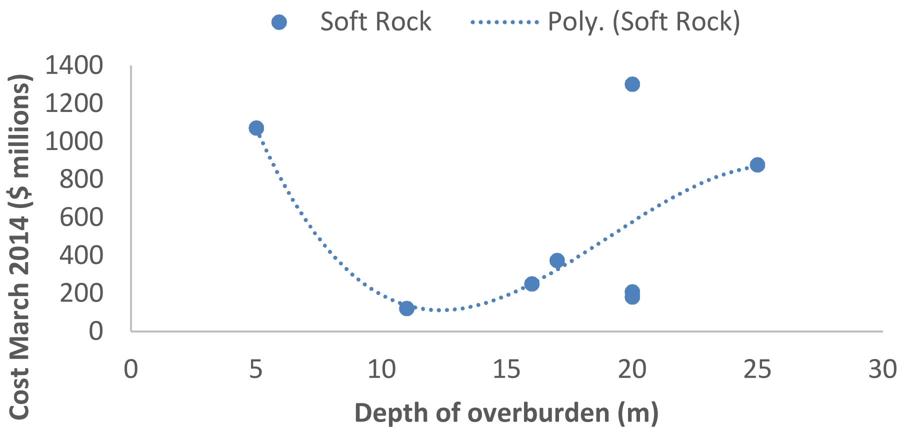

Figure 4.40. Cost against length of tunnel for the soft rock dataset

Table 4.29. Summarized fitted curves for the soft rock dataset-highways.

Excavation Method	Data points	R^2	Equation fitted to the curve
Soft rock	8	0.49	Cost = $-6416D^3 + 121543D^2 – 766329D + 2E+06$
Soft rock	8	0.94	Cost = $-0.5657L^3 + 16.708L^2 - 52.973L + 175.55$
Soft rock	8	0.45	Cost = $-0.6454De^3 + 36.829De^2 - 614.59De + 3301.4$

4.6.2.4. Geology- metro

The geology data for metro mode of transportation had 11 and 20 tunnel projects composed of hard and soft rock, respectively. In the analyses of the metro category dataset, the parameters examined were as follows: depth of overburden, tunnel diameter, tunnel length, and the total tunnel cost. The exploratory data analysis results for the parameters for the hard rock dataset for metro tunnel projects are presented in Table 4.30 and Figure 4.41.

Table 4.30. Descriptive statistics of metro system for depth, length, diameter, and cost.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	21.09	6.74	13.00	20.00	30.00	0.21	-1.34
Length (km)	4.27	4.03	1.00	4.30	14.00	1.52	2.56
Diameter (m)	6.535	2.805	3.700	5.870	12.730	1.17	1.13
Cost($millions)	221.0	191.2	23.0	192.2	687.0	1.60	3.00

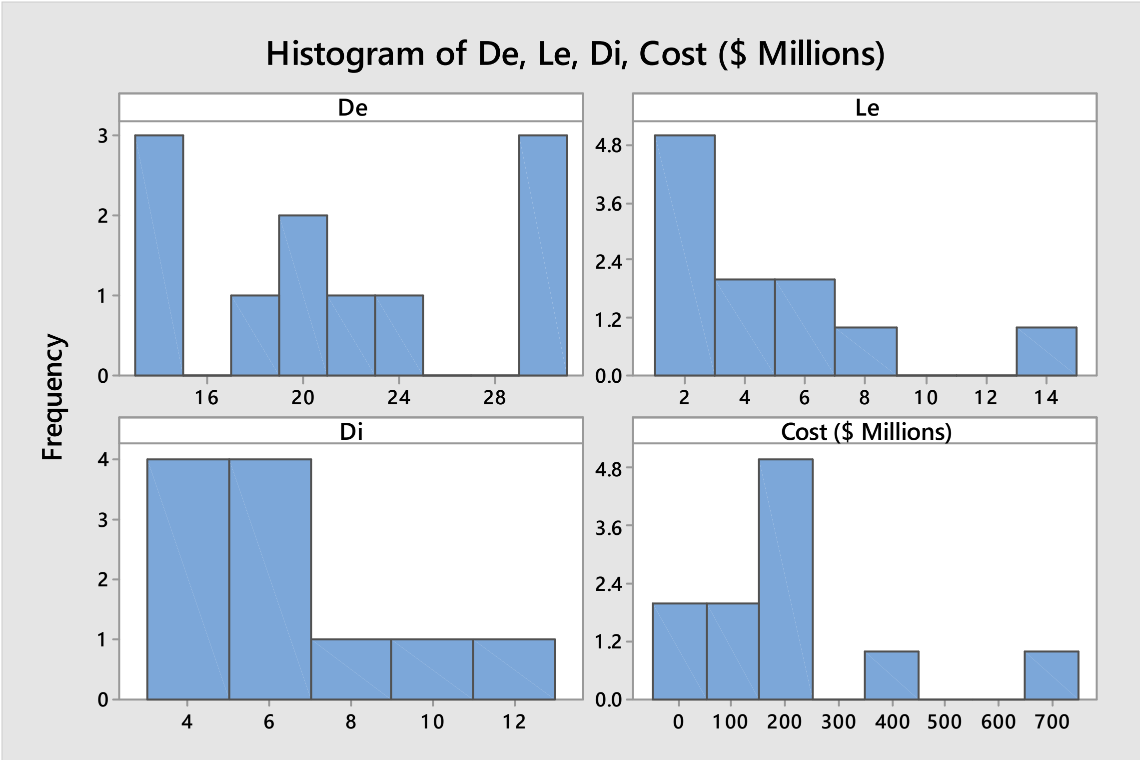

Figure 4.41. Histogram of depth, length, diameter and cost

Plots of the dependent variable (tunnel costs) against the independent variables (diameter, length, and depth) including the regression lines for hard rock for the metro mode of tunneling projects are presented. Table 4.31 presents the summary of the fitted equations for the hard rock category of the railway tunneling projects. Figures 4.42 to 4.44 show the plots of cost against diameter, length, and depth of overburden together with regression lines for the hard rock dataset.

Table 4.31. Summarized fitted curves for the hard rock dataset-highways.

Excavation Method	Data points	R^2	Equation fitted to the curve
Hard rock	10	0.21	Cost = $3.0432D^3 - 70.233D^2 + 487.26D - 846.51$
Hard rock	10	0.71	Cost = $-1.613L^3 + 31.053L^2 - 117.33L + 194.53$
Hard rock	10	0.14	Cost = $-0.0711De^3 + 4.019De^2 – 73.827De + 630.99$

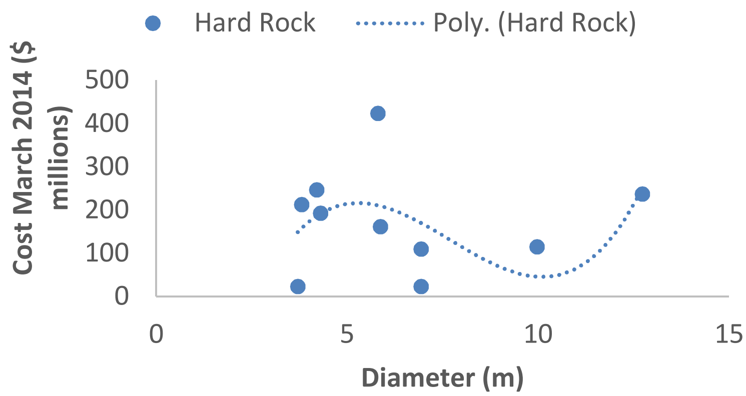

Figure 4.42. Cost against diameter of tunnel for the soft rock dataset

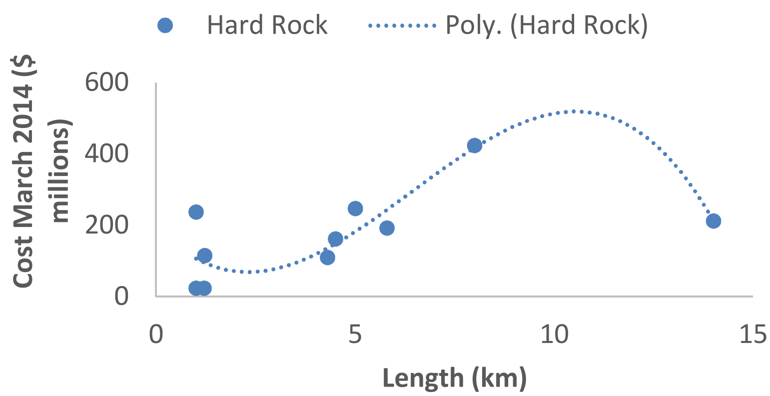

Figure 4.43. Cost against length of tunnel for the soft rock dataset

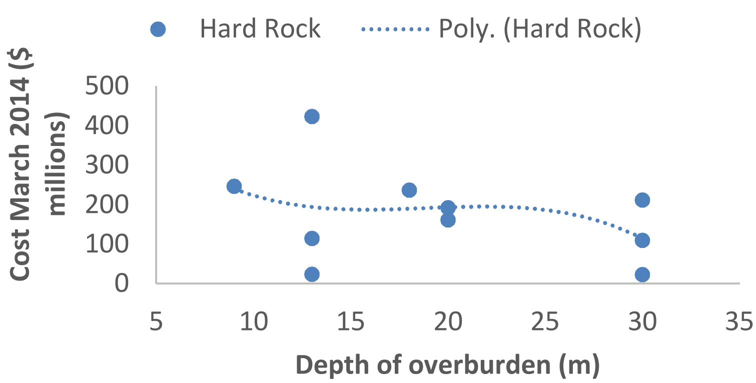

Figure 4.44. Cost against length of tunnel for the soft rock dataset

The analysis results for the soft dataset the parameters (depth of overburden, tunnel diameter, tunnel length, and the total tunnel cost) for metro tunnel projects are presented in Figure 4.45 and Table 4.32.

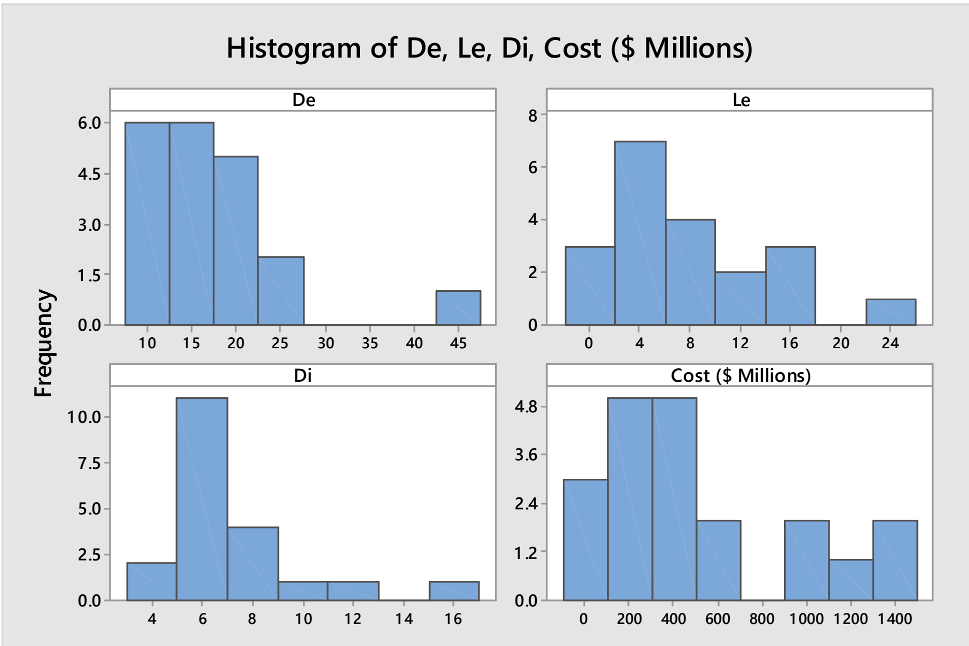

Figure 4.45. Histogram of depth, length, diameter and cost

Table 4.32. Descriptive statistics for depth, length, diameter, and cost.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	17.25	8.38	8.00	15.00	46.00	2.25	6.94
Length (km)	8.00	6.41	1.00	5.95	24.00	1.09	0.47
Diameter (m)	7.314	2.549	3.800	6.605	15.200	1.86	4.19
Cost($millions)	523.8	431.2	83.6	372.3	1475.5	1.00	-0.19

Plots of the dependent variable (tunnel costs) against the independent variables (diameter, length, and depth) including the regression lines for soft rock for the railway mode of tunneling projects are presented. Figures 4.46 to 4.48 show the plots of cost against diameter, length, and depth of overburden together with regression lines for the soft rock dataset. Table 4.33 presents the summary of the fitted equations for the soft rock category of the railway tunneling projects.

Table 4.33. Summarized fitted curves for the hard rock dataset-highways.

Excavation Method	Data points	R^2	Equation fitted to the curve
Soft rock	15	0.25	$Cost = 13.885D^3 - 292.19D^2 + 1890.1D - 3242.8$
Soft rock	15	0.37	$Cost = -1.0287L^3 + 32.573L^2 - 251.89L + 893.88$
Soft rock	15	0.26	$Cost = -1.5541De^3 + 68.42De^2 - 905.64De + 3960.8$

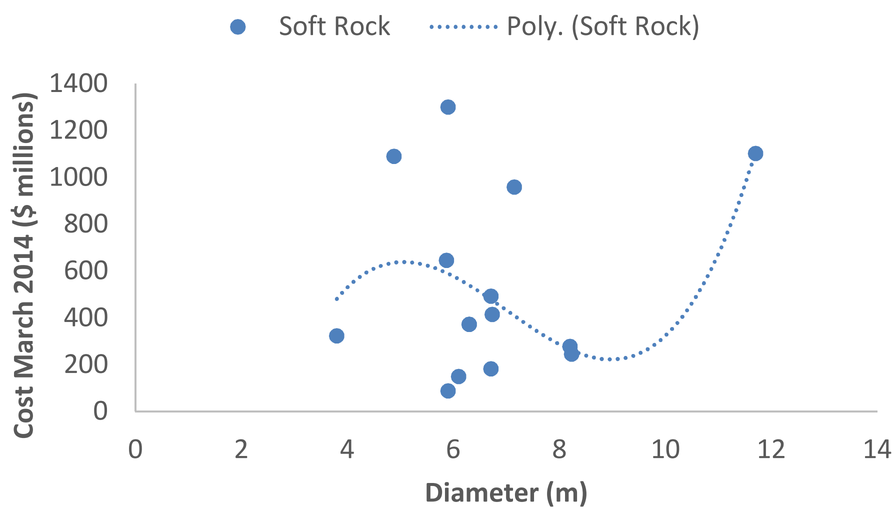

Figure 4.46. Cost against diameter of tunnel for the soft rock dataset

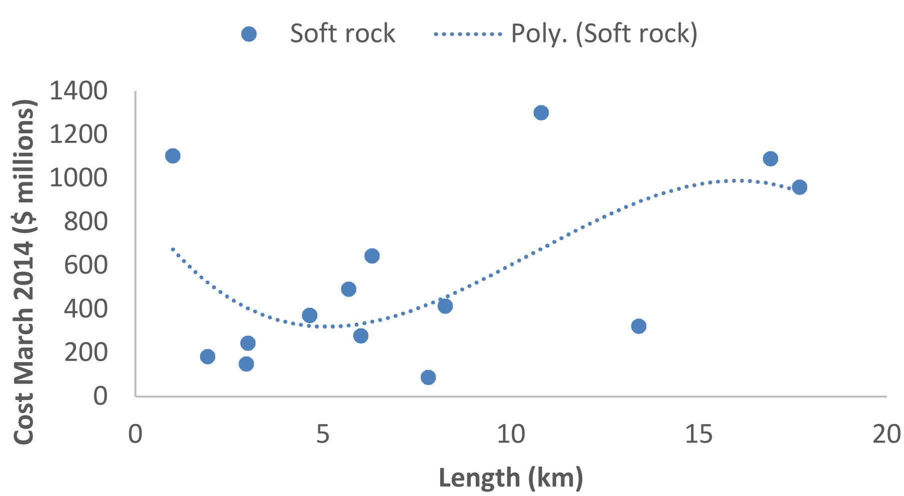

Figure 4.47. Cost against diameter of tunnel for the soft rock dataset

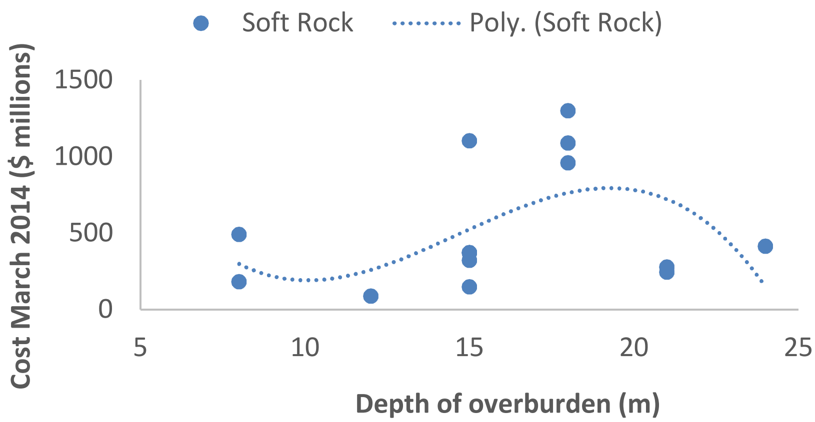

Figure 4.48. Cost against overburden depth of tunnel for the soft rock dataset

4.7. Classification of Curve Fitting Results

The resulting fitted curves based on ground conditions were classified into classes by employing the R-squared values. The classification matrix used to compare R-squared results consisted of the following classes: very strong (VS), strong (S), moderate (M), and weak (W). The very strong class indicates that the fitted curve explains most of the variability of the response data around its mean, while the weak class indicates that the fitted curve does not explain the variability of the response data around its mean. The classification used is shown in Table 4.34.

Table 4.34. Proposed classification of R-squared.

R-squared	Proposed class	Designations
R-squared < 0.25	Weak variability of the response data	W
R-squared between 0.25 and 0.50	Moderate variability of the response data	M
R-squared between 0.50 and 0.75	Strong variability of the response data	S
R-squared > 0.75	Very strong variability of the response data	VS

The classifications proposed in Table 4.34 were then used to analyze the fitted curves of the functions. On the basis of R-squared classification, the functions classified as M, S, and VS were identified for further evaluation. The classification results for the modes of transportation of the tunnel excavation methods are summarized in Table 4.35.

Table 4.35. Summary of fitted curves for tunnel excavation methods.

Mode of transportation	**Method excavation**	**Variables considered**	**R^2 class**
Highways	Drill and blast	Diameter	M
	Cut and cover	Diameter	S
	Cut and cover	Length	S
	Cut and cover	Depth	S
	Drill and blast	Length; depth of overburden	VS
Railway	Mixed methods	Diameter	W
	Mixed methods	Depth of overburden	M
	TBM	Depth of overburden	S
	TBM	Diameter; length	VS
	Mixed methods	Length	VS
Metro	Mixed methods	Diameter	M
	Mixed methods	Length	W
	Mixed methods	Depth of overburden	S
Subway	Mixed methods	Diameter, Length	W
	TBM	Diameter	W
	TBM	Length	M
	Mixed methods	Depth of overburden	M
	TBM	Depth of overburden	VS

Table 4.36 gives the classification results of fitted curves based on subsurface geology which was subdivided into soft and hard rock, and the summary of hard and soft rock datasets for the modes of transportation are shown in Table 4.37.

Table 4.36. Summary of fitted curves for hard and soft rock data.

Type of geology	Method excavation	Variables considered R^2 value	R^2 class
Hard rock	Entire dataset	Diameter, length, depth of overburden	W
Soft rock	Entire dataset	Diameter	M
		Length	S
		Depth of overburden	W

Table 4.37. Summary of fitted curves for hard and soft rock data.

Type of geology	Mode of transportation	Variables considered R^2 value	R^2 class
Hard rock	Highways	Diameter, length	M
		Depth of overburden	S
Hard rock	Railways	Diameter	S
		Length	W
		Depth of overburden	M
Soft rock	Railways	Diameter, depth of overburden	W
		Length	VS
Hard rock	Metro	Diameter, depth of overburden	W
		Length	S
Soft rock	Metro	Diameter, length, depth of overburden	M

From the classification of the functions, those functions classified as M, S, and VS were selected for further analysis. A function for a mode of transportation was selected based on the value of R-squared of the variable considered. In cases where a mode of transportation had more than one variable classification proposed for further analysis, sensitivity analysis was performed on the functions to select the best fit function. In the case of the highway mode of transportation tunnel, all the variables considered of diameter of tunnel, length of tunnel, and depth of burden were selected as the best functions for the cut and cover and drill and blast excavation methods.

4.7.1. Highway mode of transportation tunneling

Cut and cover and drill and blast were the two common methods employed. The cost estimation functions developed from the fitting of curves to the variables were classified as M, S and VS. The results showed a positive trend in the case of tunnel cost estimate and the variables considered for the two tunnel excavation methods. Figures 4.49 and 4.50 show the precision of the predicted cost versus actual cost. A sensitivity analysis was performed on the fitted functions to determine the best equation to use. The precision test determined the ratio of the predicted cost to the actual cost. The cost estimate function showed a higher precision when the ratio of the predicted cost to actual cost is closer to 1.00.

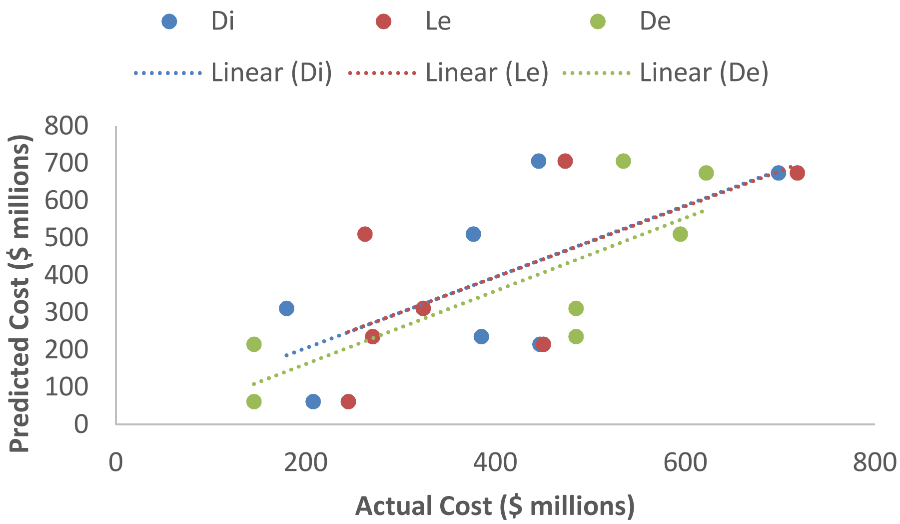

Figure 4.49. Predicted cost vs. actual cost for cut and cover highway excavation method

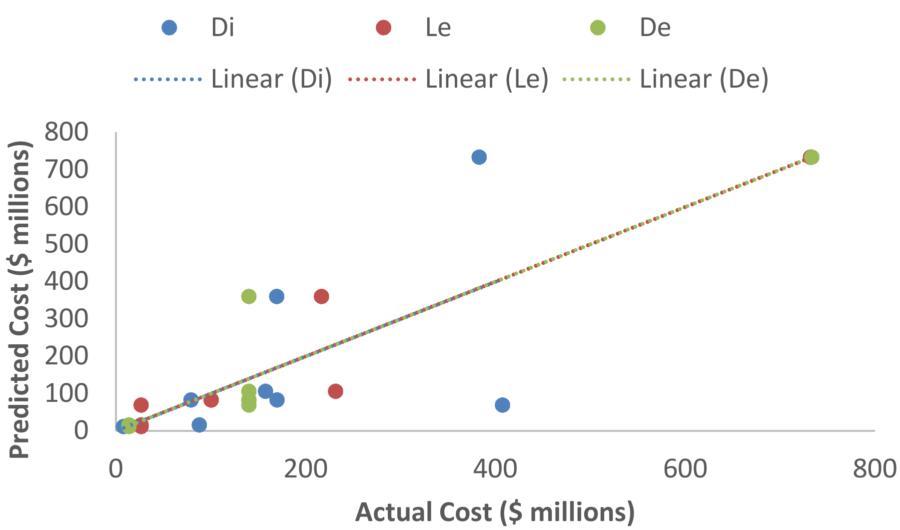

Figure 4.50. Predicted cost vs. actual cost for drill and blast highway excavation method

Figure 4.49 shows the slopes for the curvilinear cost functions for depth of overburden and diameter of tunnel with a precision of 0.978 and 0.955 respectively. It also shows any function between the two can be employed; however depth of overburden will give the best results because the slope is closer to 1.00 which reflects the best accuracy in prediction. In Figure 4.50 shows that the slopes of the functions are almost the same. The length of tunnel and depth of overburden gave the best results with slope at 1.00. Figure 4.50 shows that any function between the two functions developed can be employed with the best results obtained when the length of tunnel for the drill and blast highway tunnel excavation method is used.

4.7.2. Railway mode of transportation tunneling

In this category, two methods were considered for the precision analysis test. The two methods were mixed and TBM tunnel excavation methods. For the mixed methods, depth of overburden and length were analyzed, while all three variables were analyzed for the TBM method. The precision analysis test results for the two methods are depicted in Figure 4.51 and 4.52.

Figure 4.51 shows the slopes for the curvilinear functions for depth of overburden and length of tunnel with a precision of 1.07 and 1.05 respectively. The slope values for the length of tunnel function as a better fit because the slope is closer to 1 which reflects the best accuracy in prediction. In addition, Figure 4.51 indicates that the function is more powerful as it traces the data when performing sensitivity analysis. Figure 4.52 shows the slopes of diameter of tunnel, length of tunnel, and depth of overburden functions the mixed railway tunnel excavation method. The slopes values for the mixed railway excavation tunnel excavation function for the diameter of tunnel, length of tunnel, and depth of overburden functions are 0.84, 0.93, and 0.21 respectively. The slope of the length of tunnel function gave the best results with a slope near 1.00. In addition, it traces the data when performing sensitivity analysis. Also, it is the function that can be employed with the best results for the mixed highway tunnel excavation method.

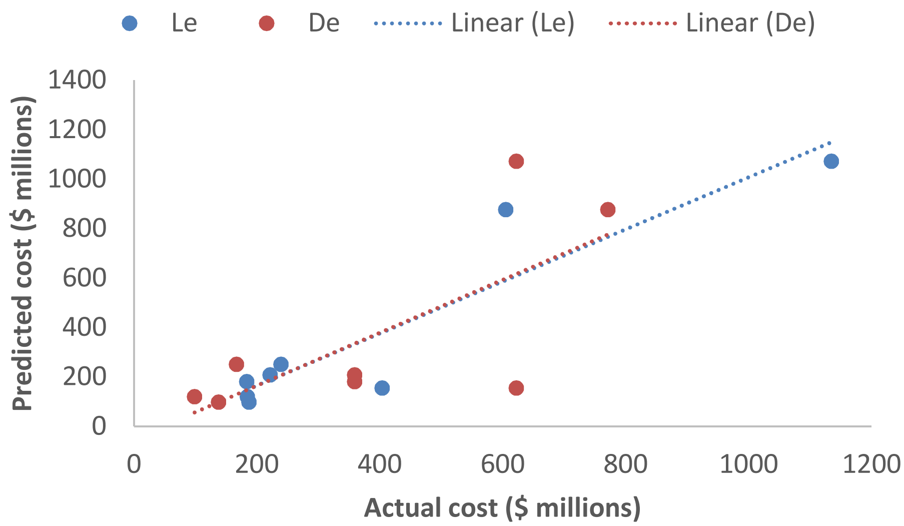

Figure 4.51. Predicted cost vs. actual cost for mixed railway tunnel excavation method

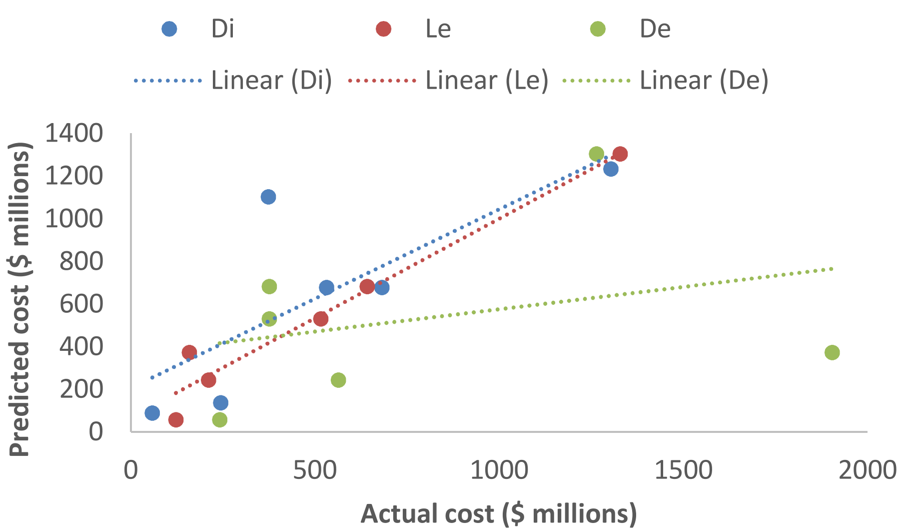

Figure 4.52. Predicted cost vs. actual cost for TBM railway tunnel excavation method

4.7.3. Metro mode of transportation tunneling

In this category, one method was considered for the precision analysis test. The method considered was the mixed tunnel excavation methods. Data for other types of tunnel excavation methods was not sufficient to fit the curves. For the mixed methods, depth of overburden and diameter of tunnel were analyzed. The precision analysis test result for the methods is presented in Figure 4.53.

Figure 4.53 shows the slopes of depth of overburden and diameter of tunnel functions for the mixed metro tunnel excavation methods. The slope values for the railways mixed tunnel excavation functions for the depth of overburden and diameter of tunnel are 1.00 and 1.2 respectively. The slope of the depth of overburden function gave the best results with the slope at 1.00. In addition, it traces the data when performing sensitivity analysis. Also, it is the function that can be employed with the best results for the mixed highway tunnel excavation method.

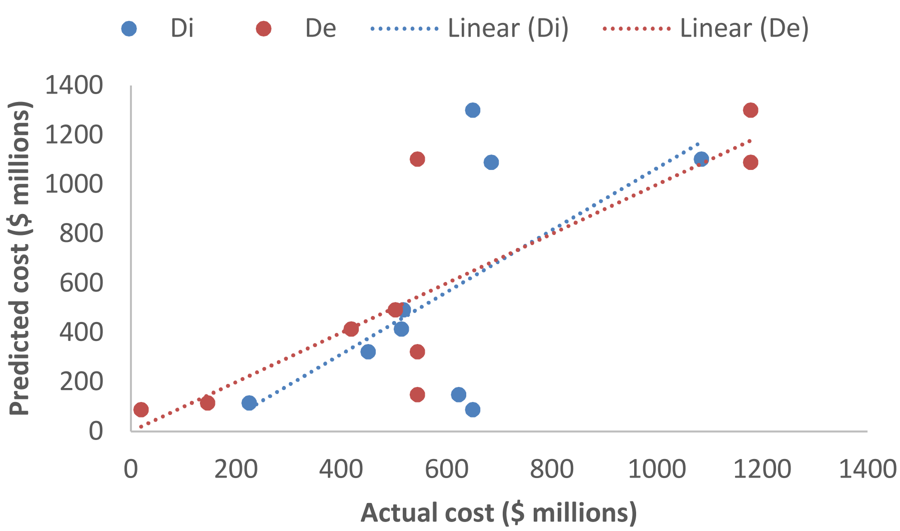

Figure 4.53. Predicted cost vs. actual cost for mixed metro tunnel excavation methods

4.7.4. Subway mode of transportation tunneling

In this category, two methods were considered for the precision analysis test. The two methods were mixed and TBM tunnel excavation methods. For both methods, depth of overburden and length were analyzed. The precision analysis test results for the two methods are depicted in Figures 4.54 and 4.55.

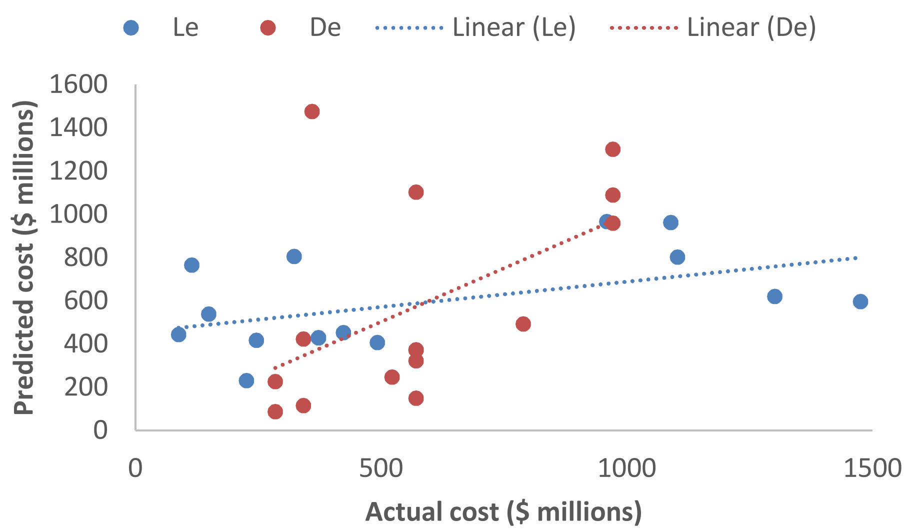

Figure 4.54. Predicted cost vs. actual cost for mixed subway tunnel excavation methods

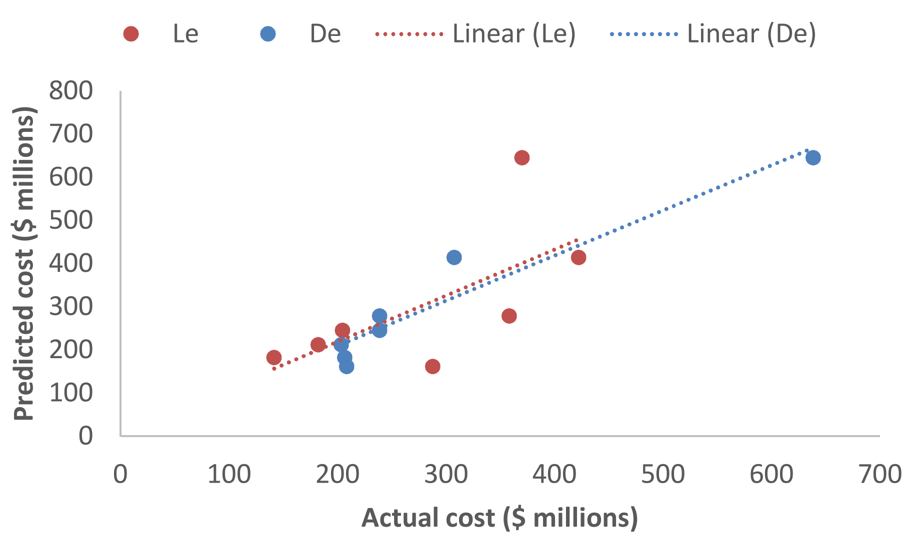

Figure 4.55. Predicted cost vs. actual cost for TBM subway tunnel excavation method.

Figure 4.53 shows the slopes for the curvilinear functions for depth of overburden and length of tunnel with a precision of 0.992 and 0.24 respectively. The slope values for the depth of overburden function give a better fit because the slope is closer to 1.00, which reflects the best accuracy in prediction. It indicates that the function does not trace the data accurately when performing sensitivity analysis. However, it is the only function developed that does not underestimate project cost estimate and the best function for mixed railway tunnel excavation methods. Figure 4.55 presents the slope values for the TBM subway excavation tunnel excavation method for the length of tunnel and depth of overburden functions as 1.07 and 1.04, respectively. It indicates that both length of tunnel and depth of overburden subway cost functions overestimate the cost estimate based on the slope values. This problem is due to the small number of tunnel projects used to develop the function. The depth of overburden function traces the data when performing sensitivity analysis. This function can be employed as it provides the best results for the TBM subway excavation method.

4.8. Modes of Transportation Tunnels

In the tunnel application category, both subways and metro tunnel projects were combined because they are similar. Railways and light rail projects were also combined due to their low numbers. Based on the application category, the tunnels were classified into highways, subways, and railways. Figure 4.56 shows the percentage distribution of tunnel applications available in the database. The subway classification had the highest percentage distribution at 39%.

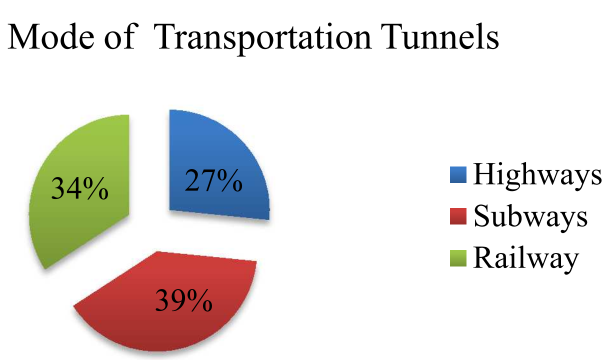

Figure 4.56. Tunnel applications available in the database

4.8.1. Highways

A total of 21 tunnel projects constructed between 1991 and 2014 was compiled on the highways category. Preliminary data analysis was performed on the following parameters: depth of overburden, diameter of tunnel, total cost of tunnel project, and tunnel project cost per meter. When the histogram plot was developed, the observations shown in Figure 4.57 were made. The descriptive statistics for depth of overburden, diameter, length of tunnel, and total tunnel cost are shown in Table 4.38. The mean depth of overburden is 9.11 m and the median is 8.00 m. The one-point difference between the mean and median is an indication of variation of the dataset from the normal. The dataset is negatively skewed. The maximum depth of overburden is 27.00 m. For the diameter variable, the mean tunnel diameter is 8.963 m with a standard deviation of 3.417 m. The median was 6.930 m compared with a mean of 8.963 m, an indication of the dataset being left-skewed. For length and total cost, the average mean was 4.07 m, and $306 million and standard deviations of 5.99 m and $245.9 million respectively. Other pertinent statistics for depth of overburden, length, diameter, and cost are presented in Figure 4.57 and Table 4.38.

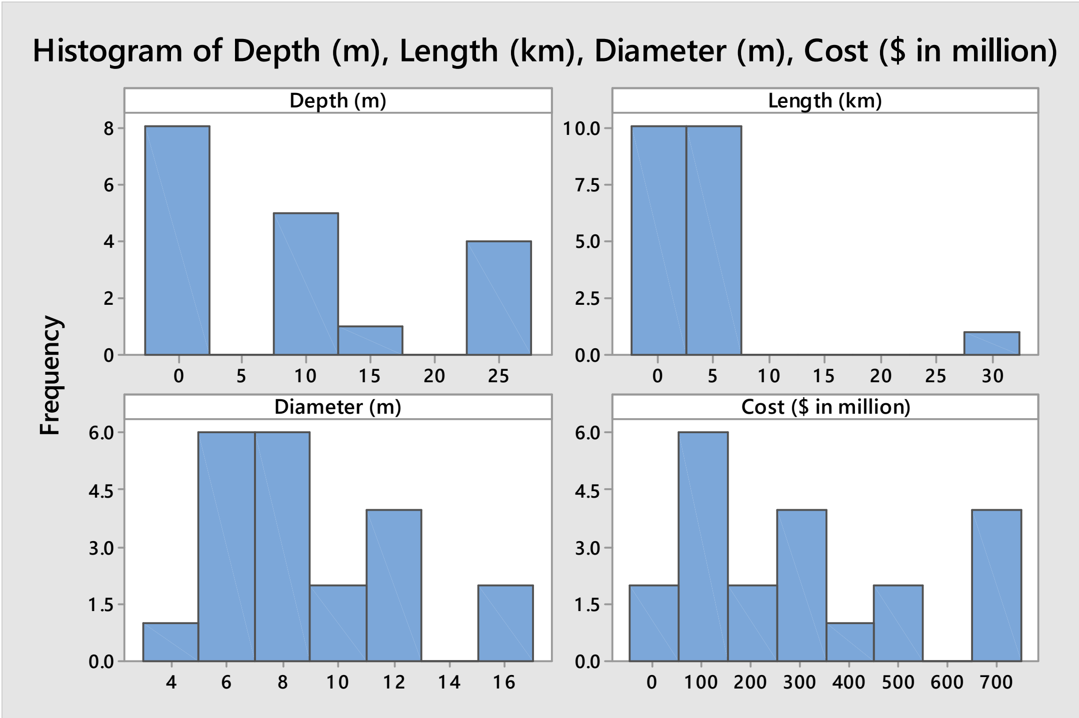

Figure 4.57. Histogram of depth, length, diameter and cost

Table 4.38. Descriptive statistics for depth, length, diameter, and cost in millions dollars.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	9.11	10.52	0.00	8.00	27.00	0.82	-0.83
Length (m)	4.07	5.99	1.00	2.50	29.10	4.00	17.17
Diameter (m)	8.963	3.417	4.600	7.830	16.420	0.87	0.11
Cost($millions)	306.2	245.9	11.2	292.3	746.5	0.65	-081

A plot of tunnel cost against the variables (diameter of tunnel, length of tunnel, and depth of overburden) for the highway mode of transportation is presented in Figure 4.58. Figure 4.58 shows the fitted curves for the highway dataset. The correlation coefficients of tunnel cost functions for this type of tunnel were 43%, 37%, and 44% for diameter of tunnel, length of tunnel, and depth of overburden, respectively. Also, a multi-variable analysis was performed on the highway dataset. The functions developed had correlation coefficients for this type of 34% and 33.7% for the two equations considered. Subsequently, Table 4.39 illustrates the summary of analyses for the highway mode of transportation.

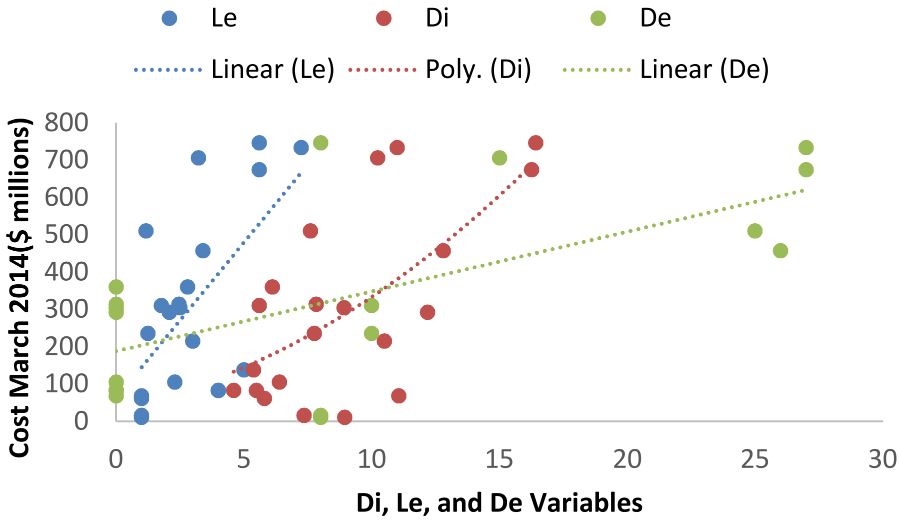

Figure 4.58. Tunnel cost vs diameter, length, and depth of overburden for highway tunnels

Table 4.39. Summary of tunnel cost and multi-variable analyses for highway tunnels.

Highway tunnels	R^2	Equation fitted to the curve
Diameter	0.43	Cost = 1.6623Di^2 + 12.816Di + 39.248
Length	0.37	Cost = 83.512Le + 61.991
Depth of overburden	0.44	Cost = 16.017x + 188.15
Regression function 1	0.34	Cost = e^(4.29 + 0.127Le + 0.017Di + 0.017Le*Di)
Regression function 2	0.33	Cost = e^(3.654 + 0.302Le + 0.0852Di)

The precision analysis test of predicted cost versus actual cost for the highway tunnels is presented in Figure 4.59. It shows the slopes of the tunnel functions for highway tunnels shown in Table 4.39. Figure 4.59 shows the slopes of diameter of tunnel, length of tunnel, depth of overburden, and the two regression equations as 0.43, 0.36, 0.46, 0.82, and 0.77, respectively. In general, the slope closer to 1.00 shows the better accuracy in the prediction. The functions developed through multi-variable analysis showed better accuracy for the tunnel cost estimation.

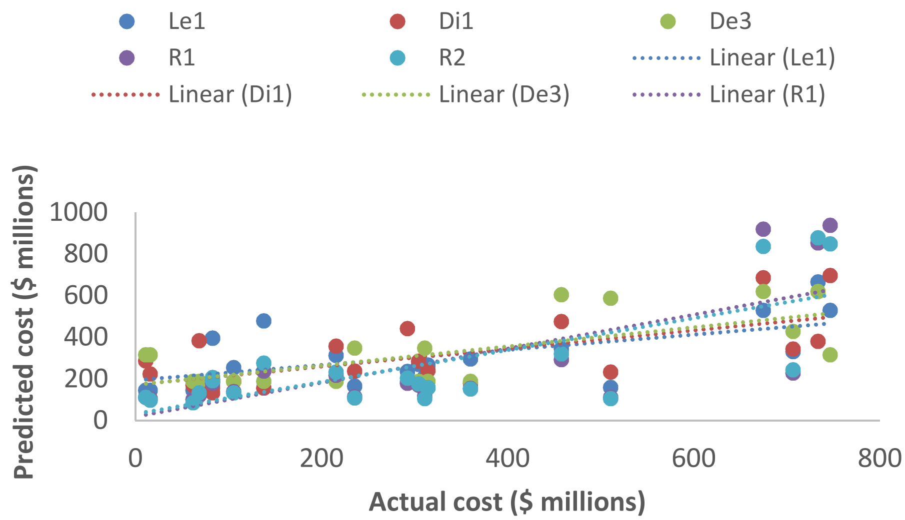

Figure 4.59. Predicted cost vs. actual cost for highway tunnels

4.8.2. Subways

The subways dataset compiled had 18 tunnel projects constructed between 1991 and 2015. The parameters analysed were depth of overburden, diameter of tunnel, total cost of tunnel project, and tunnel project cost per meter. Histogram presentation for these analysed parameters is shown in Figure 4.60. Descriptive statistics for depth of overburden, diameter, length of tunnel, and total tunnel cost are shown in Table 4.40. The dataset shows the average depth of overburden for the subway was 16.22 m with a standard deviation of 4.58 m. The median is 16.50 m which shows a deviation from the mean of 16.22 m an indication that the dataset is slightly skewed. For the diameter, the average tunnel diameter is 7.51 m with a standard deviation of 3.03 m. The median was 6.71 m compared with a mean of 7.51 m, an indication of the dataset being left-skewed. For length and total cost, the average mean was 6.80, and $458.5 million and standard deviations of 5.81 m and $404.4 million respectively. Other pertinent statistics for depth of overburden, length, diameter, and cost are presented in Figure 4.60 and Table 4.40.

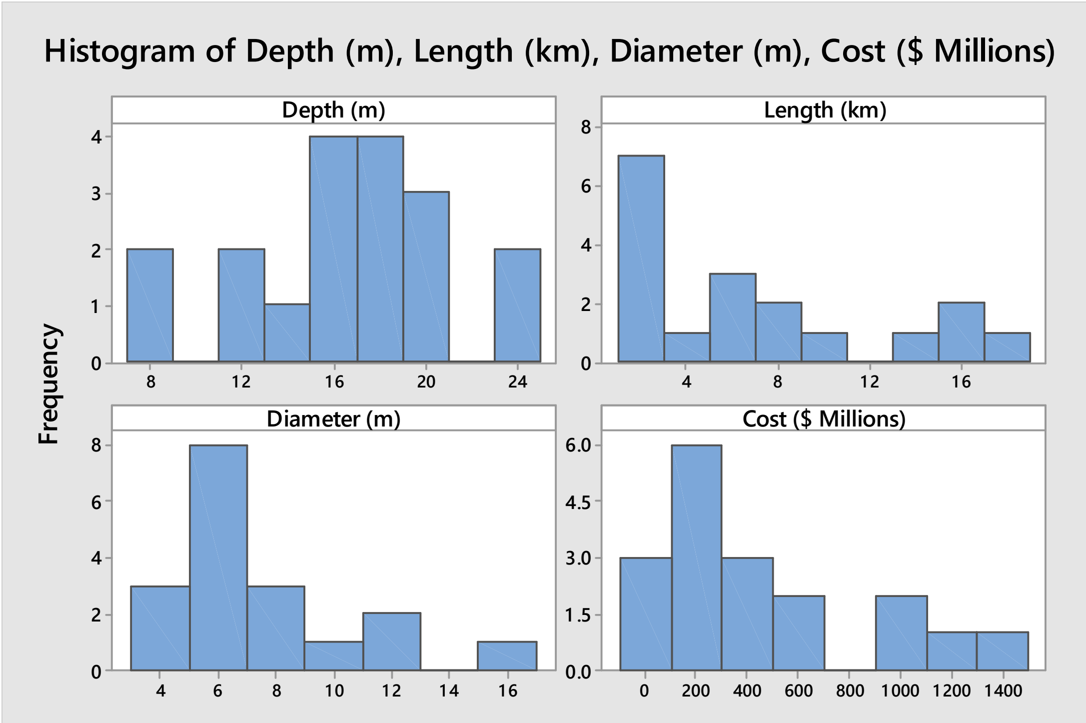

Figure 4.60. Histogram of depth, length, diameter and cost

Table 4.40. Descriptive statistics for depth, length, diameter, and cost in millions dollars.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	16.22	4.58	8.00	16.50	24.00	-0.14	-0.25
Length (m)	6.80	5.81	1.00	5.74	17.68	0.75	-0.75
Diameter (m)	7.51	3.03	3.80	6.71	15.20	1.34	1.34
Cost($millions)	458.5	404.4	83.6	279.9	1301.1	0.95	-0.47

A plot of tunnel cost against the variables (diameter of tunnel, length of tunnel, and depth of overburden) for the subway tunnels mode of transportation is presented in Figure 4.61. Figure 4.61 shows the fitted curves for the subway tunnels dataset. The correlation coefficients of tunnel cost functions for this type of tunnel were 0.6%, 16%, and 9% for diameter of tunnel, length of tunnel, and depth of overburden, respectively. Also, a multi-variable analysis was performed on the subway dataset. The functions developed had correlation coefficients of 95% and 15% for two equations considered for this type of tunnels. Subsequently, Table 4.41 illustrates the summary of analyses for the subway mode of transportation.

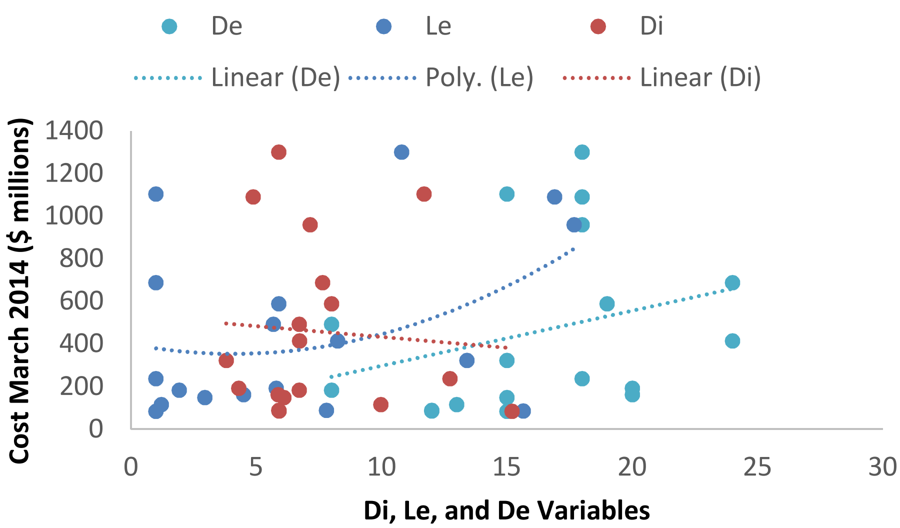

Figure 4.61. Tunnel cost vs diameter, length, and depth of overburden for subway tunnels

Table 4.41. Summary of tunnel cost and multi-variable analyses for subway tunnels.

Subway tunnels	R^2	Equation fitted to the curve
Diameter	0.006	Cost = -10.167Di + 534.88
Length	0.16	Cost = $2.6712Le^2$ - 21.908Le + 398.75
Depth of overburden	0.09	Cost = 25.865De + 38.919
Regression function 1	0.95	Cost = e^(0.0863De + 0.2121Le + 0.3494Di)
Regression function 2	0.15	Cost = e^(4.786 + 0.0377De + 0.0332Le)

The precision analysis test of predicted cost versus actual cost for the subway tunnels is presented in Figure 4.62. The slopes of the tunnel functions for subway tunnels are shown in Table 4.41. Figure 4.62 shows the slopes of diameter of tunnel, length of tunnel, depth of overburden, and the two regression equations as 0.006, 0.16, 0.09, 0.53, and 0.09, respectively. In general, the slope closer to 1.00 shows the better accuracy in the prediction. Although, the functions developed through multi-variable analysis showed better accuracy for the tunnel cost estimation, however, the equations did not yield the best results were performing precision analysis. The precision analysis results for the equations given in Table 4.41 ranged from 0.006

to 0.53. The best function for the subway tunnels explained only 13.8% of the variability response data. Figure 4.62 indicates that the functions developed underestimate the tunnel cost on the basis of slope. Regression function R2 could only be used to predict tunnel cost for subway tunnels in cases where tunnel methods of excavation or type of geology functions are inapplicable.

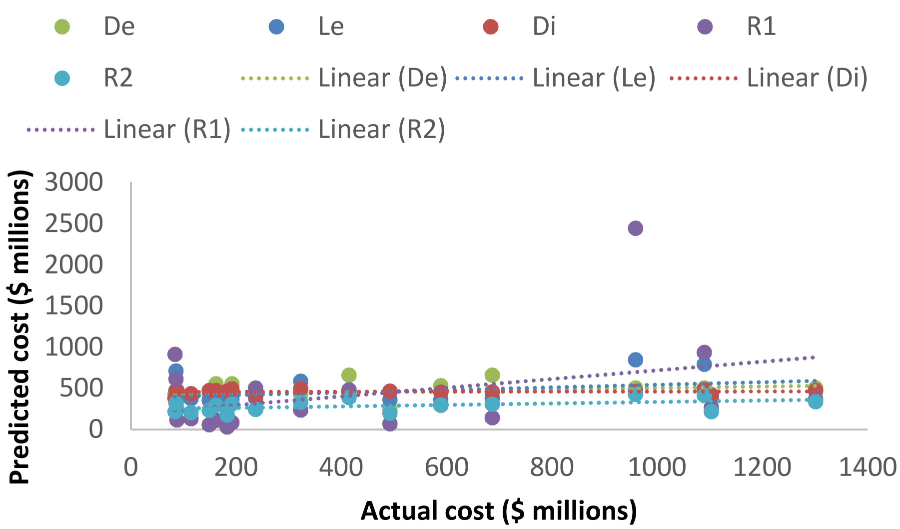

Figure 4.62. Predicted cost vs. actual cost for subway tunnels

4.8.3. Railways

This mode of transportation contained 27 tunnel projects constructed between 1985 and 2015. Statistical analysis was performed for depth of overburden, diameter of tunnel, total cost of tunnel project, and tunnel project cost per meter. When the histogram plot was developed for the parameters analyzed, observations shown in Figure 4.63 were made. The descriptive statistics for the parameters are shown in Table 4.42. Depth of overburden analysis for the railway dataset shows that the average was 23.96 m with a standard deviation of 13.29 m. The median was 22.50 m which shows a deviation from the mean of 23.96 m an indication that the dataset is slightly skewed. For the diameter, the average tunnel diameter was 6.894 m with a standard deviation of

2.766 m. The median was 6.400 m compared with a mean of 6.894 m, an indication of the dataset being left-skewed. For length and total cost, the average of 6.19 and $884 million, and standard deviations of 5.07 m and $244 million respectively. Other pertinent statistics for depth of overburden, length, diameter, and cost are presented in Figure 4.63 and Table 4.42.

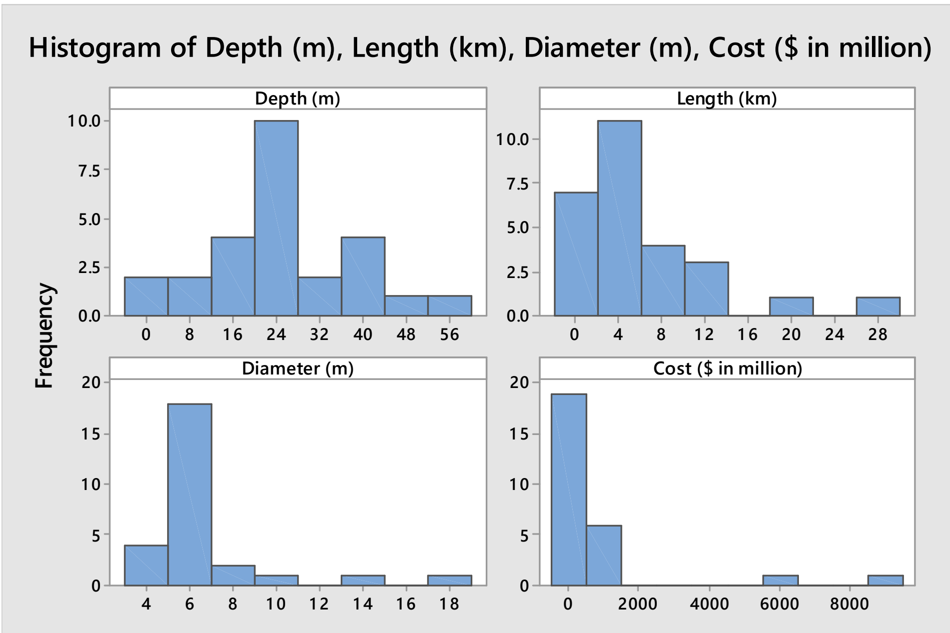

Figure 4.63. Histogram of depth, length, diameter and cost

Table 4.42. Descriptive statistics for depth, length, diameter, and cost in millions dollars.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	23.96	13.29	0.00	22.50	57.00	0.48	0.72
Length (m)	6.19	6.34	1.00	5.07	28.00	1.98	4.64
Diameter (m)	6.894	2.766	3.250	6.400	17.200	2.42	7.58
Cost($millions)	884	1997	28	244	9090	3.55	12.56

A plot of tunnel cost against the variables of diameter of tunnel, length of tunnel, and depth of overburden for the railway tunnels mode of transportation is presented in Figure 4.64. Figure 4.64 shows the fitted curves for the railway tunnels dataset. The correlation coefficients of tunnel cost functions for this type of tunnel were 3%, 73%, and 10% for diameter of tunnel, length of tunnel, and depth of overburden, respectively. In addition, a multi-variable analysis was performed on the subway dataset. When performing the analyses, the functions developed had correlation coefficients of 63% and 61% for two equations considered for this type of tunnels. Subsequently, Table 4.43 illustrates the summary of analyses for the railway tunnels mode of transportation.

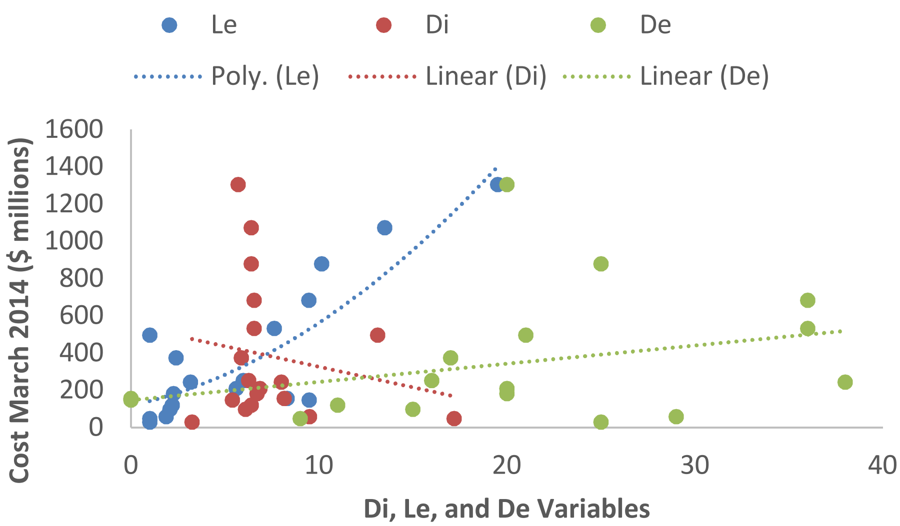

Figure 4.64. Tunnel cost vs diameter, length, and depth of overburden for railway tunnels

Table 4.43. Summary of tunnel cost and multi-variable analyses for railway tunnels.

Subway tunnels	R^2	Equation fitted to the curve
Diameter	0.03	Cost = -22.063Di + 546.84
Length	0.73	Cost = 2.2489Le^2 + 21.962Le + 117.68
Depth of overburden	0.10	Cost = 9.7818De + 146.95
Regression function 1	0.63	Cost = e^(3.197 + 0.0443De + 0.1815Le + 0.0504Di)
Regression function 2	0.61	Cost = e^(3.669 + 0.0427De + 0.1709Le)

The precision analysis test performed on predicted cost versus actual cost for the railway tunnels is presented in Figure 4.65. It shows the slopes of the tunnel functions of the variables in diameter of tunnel, length of tunnel, depth of overburden for subway tunnels. The slopes of the functions were 0.03, 0.73, 0.02, 1.29, and 1.23. The slope closer to 1.00 in general provides a better accuracy in prediction of cost. The length and multi-variable analysis functions showed better accuracy for the tunnel cost estimation. The precision analysis results for the equations ranged from 0.02 to 1.29. Figure 4.65 indicates that the functions developed underestimate the tunnel cost on the basis of slope, while the regression functions overestimate tunnel cost. Regression functions could be employed to estimate cost for railway tunnels.

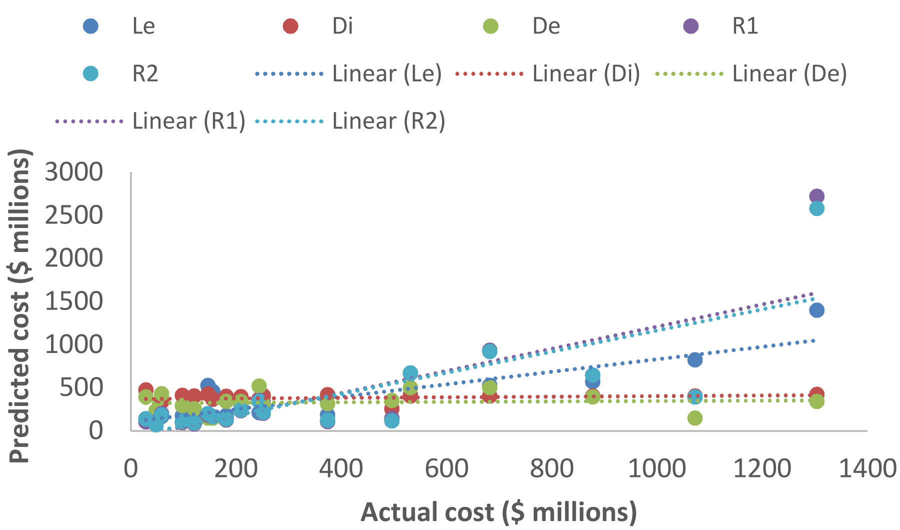

Figure 4.65. Predicted cost vs. actual cost for railway tunnels

4.8.4. Combined subway and metro tunnels

The subways dataset compiled had 31 tunnel projects constructed between 1991 and 2015. The parameters analysed were depth of overburden, diameter of tunnel, total cost of tunnel project, and tunnel project cost per meter. A histogram presentation for these parameters analysed is shown in Figure 4.66. Descriptive statistics results for the variables are shown in Table 4.44. The dataset shows the average depth of overburden for the subway was 17.72 m with a standard deviation of 8.39 m. The median is 16.50 m which shows a deviation from the mean of 17.72 m an indication that the dataset is slightly skewed. For the diameter, the average tunnel diameter is 17.21 m with a standard deviation of 8.40 m. The median was 15.00 m compared with a mean of 17.21 m; an indication of the dataset being left-skewed. For length and total cost, the average mean was 6.68, and $416.3 million and standard deviations of 5.89 m and $389.4

million respectively. Other pertinent statistics for depth of overburden, length, diameter, and cost are presented in Figure 4.66 and Table 4.44.

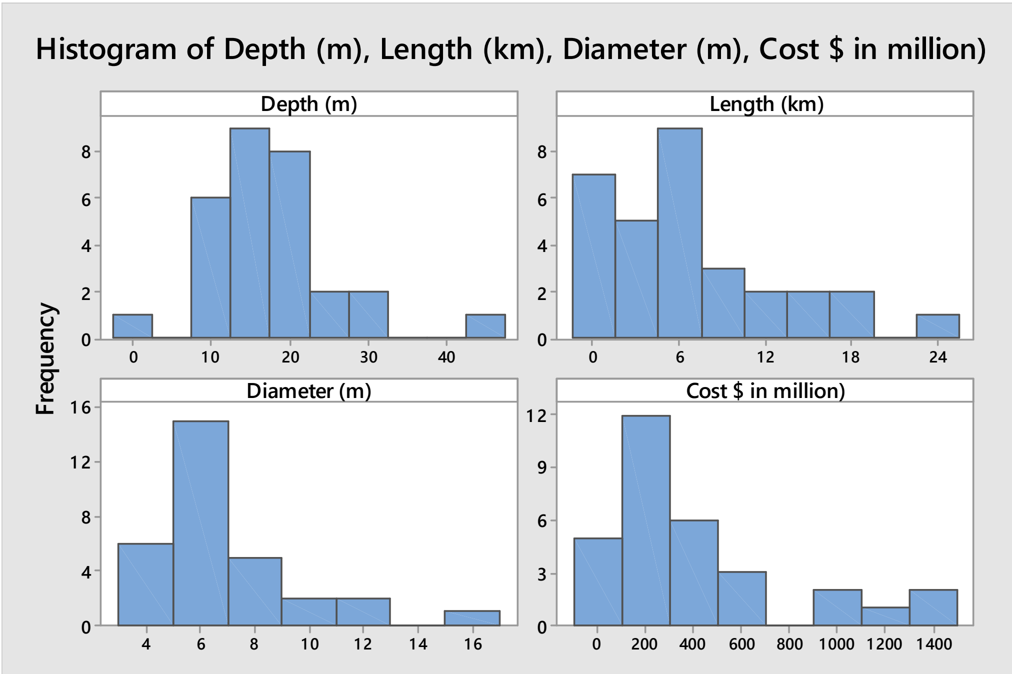

Figure 4.66. Histogram of depth, length, diameter and cost

Table 4.44. Descriptive statistics for depth, length, diameter, and cost in millions dollars.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	17.21	8.40	0.00	15.00	46.00	1.36	4.23
Length (m)	6.68	5.89	1.00	5.00	24.00	1.31	1.26
Diameter (m)	7.038	2.623	3.700	6.500	15.200	1.42	2.38
Cost($millions)	416.3	389.4	23.0	246.4	1475.5	1.40	1.13

A plot of tunnel cost against the variables of diameter of tunnel, length of tunnel, and depth of overburden for the combined subway and metro modes of transportation is presented in Figure 4.67. Figure 4.67 shows the fitted curves for the combine subway and metro tunnels dataset. The correlation coefficients of tunnel cost functions for this type of tunnel were 3%, 73%, and 10% for diameter of tunnel, length of tunnel, and depth of overburden, respectively. In addition, a multi-variable analysis was performed on the subway dataset. When performing the analyses, the functions developed had correlation coefficients of 63% and 61% for two equations considered for this type of tunnels. Subsequently, Table 4.45 illustrates the summary of analyses for the railway tunnels mode of transportation.

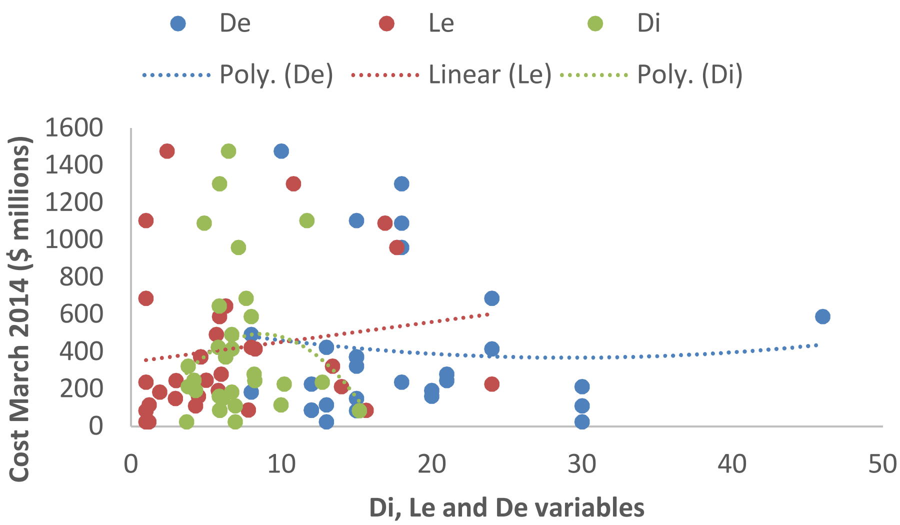

Figure 4.67. Tunnel cost vs diameter, length, and depth of overburden for railway tunnels

Table 4.45. Summary of tunnel cost and multi-variable analyses for railway tunnels

Subway tunnels	R^2	Equation fitted to the curve
Diameter	0.04	Cost = $-8.4884Di^2 + 146.99Di - 141.16$
Length	0.03	Cost = $10.765Le + 344.48$
Depth of overburden	0.01	Cost = $0.252De^2 - 14.739De + 583.57$

The equations developed for the combined subway and metro modes of transportation dataset did not yield goods results. The variables of diameter of tunnel, length of tunnel, and the depth of overburden gave poor results of coefficient of determination as presented in Table 4.45. Therefore, the function developed could be classified as weak because the R-squared is less than 0.25. Functions developed through multivariable regressions had similar attributes to those in Table 4.45 and were not considered further. In this case, functions developed for other applications that produced quality results could be used to predict costs for subways and metro modes of transportation if the need arises.

4.9. Summary

The following variables of length of tunnel, diameter of tunnel, and depth of overburden were used to develop functions that could be applied to investigate a cost estimate for a transportation tunnel project. The study used historical data to develop cost functions for different applications. The tunnels were subdivided into mode of transportation and type of geology and analyzed based on method of tunnel excavation. For the highway mode of transportation, cut and cover and drill and blast were the excavations methods commonly used. In the case of cut and cover tunnel excavation method, depth of overburden and diameter of tunnel variables used to develop the functions gave the best fitting functions that could be used to calculate tunnel cost estimate. In the drill and blast excavation method, length of tunnel and depth of overburden variables gave the best fitting results.

For the railway mode of transportation, mixed and TBM tunnel excavation methods were commonly used. In both tunnel excavation methods, the best function was developed on the basis of length. For the metro mode of transportation, mixed methods were commonly applied and did not give good results although the depth of overburden could be used. For the subway mode of transportation, mixed and TBM were the methods used. For this mode, the depth of overburden function could be used for TBM method. Type of geology for the mode of transportation did not yield good results. The only positive results were for the railway mode of transportation in soft rock and the metro mode of transportation in hard rock, where the best function was developed on the basis of length.

CHAPTER 5. PARAMETRIC COST ESTIMATION FUNCTIONS FOR TRANSPORTATION TUNNELING PROJECTS

5.1. Abstract

The influential factors such as engineering and construction complexities, poor estimating, economic and market conditions, environmental requirements, undefined scope, new technologies, risky nature of geological conditions and others were identified by a systematic literature review as the major contributors to cost and schedule overruns for transportation tunnel projects at the feasibility phase. The research paradigm described in Chapter 3 and the exploratory data analysis conducted in Chapter 4 were used to develop procedures and tools to address the problems of cost underestimation in tunnel projects. In the present work, parametric cost estimation equations termed tunnel cost estimation functions for soft and hard rock are developed. To evaluate the robustness and appropriateness of the parametric functions developed, the following statistical parameters: the R-squared value, the adjusted R-squared value, the p-value of the null hypothesis, the standard error of the coefficients, and the sum of squares of regression, and the variance of inflation factor of the functions were determined. The proposed parametric functions provided realistic results (-60% to +110%), which compared well with Class 5 of AACE International of -50% to +100% at the screening or feasibility phase of a transportation tunnel project.

5.2. Introduction

Transportation infrastructure projects involve new project developments, rehabilitations as well as the reconstruction of tunnels, highways, and railway networks. In the planning or feasibility phase of a tunnel project, fairly accurate estimates are needed for effective decision making related to bid price/project budget and construction schedule. Transportation tunnel projects are major and expensive undertakings (Reilly and Brown, 2004; Associated Press [AP], 2007; Shane et al., 2009; De Place, 2009; Efron and Read, 2012). As such the process of calculating a cost estimate for a transportation tunnel project using traditional cost estimating techniques is challenging and complicated (Romero and Stolz, n.d.). As critical as this process is, cost estimating at the feasibility phase is based on a client's broad design with limited data and several unknown factors. Moreover, these unknown factors could impact the estimate leading to under- or overestimating the cost of transportation tunnel projects. A cost estimate, also termed predesign or preliminary estimate, is used as a baseline for determining project suitability, comparing various alternatives, and establishing a budget (Sonmez, 2004). The estimates produced are then used by decision makers and the public to make multi-million or multi-billion dollar investment decisions. The estimates are also used by contractors, designers, and financial institutions for various purposes (Fragkakis et al. 2011).

Transportation tunnels are complex, engineered, underground infrastructure projects. Constructing a tunnel project involves a variety of construction activities such as excavation of rock and/or earth, removal of muck, temporary and permanent structures, tunnel lining, ventilation systems, lighting, water reticulation, and road structure or railway line. In the past, the cost estimating process for these projects resulted in significant cost and schedule underestimation ranging from about 30% to more than 50% (Reilly and Brown, 2004). In recent studies, transportation tunneling projects have experienced even more substantial cost overruns as shown in the following sample: the Seattle-Area Tunnel, the Holland Tunnel, and the Boston Central Artery/Tunnel at 49% (under construction), 300%, and 470% higher respectively (Associated Press [AP], 2007; Shane et al., 2009; De Place, 2009). Cost estimation is further compounded by project complexity, undefined/unknown scope, new technologies, and the risky nature of underground construction conditions (Hertogh et al., 2008; Efron and Read, 2012). It is the aforementioned factors that make the cost estimation process complex and challenging during the feasibility phase due to inherent uncertainty and limited data to compute realistic estimates for project sponsors and contractors involved. Utilizing traditional cost estimation techniques and incomplete data also affects the accuracy of an initial cost estimate (Chou, 2011) undermining its main objective of establishing budget for the project, and as a tool that can be used for planning and cost control. Incomplete or missing data may occur because of participants not responding to questions, data entry errors, and in some cases, due to elimination of outliers. Incomplete data is a problem because nearly all the statistical methods assume complete information for all the variables included in the analysis. The results of incomplete data of some variables used in the analysis could substantially reduce the sample size.

In traditional cost estimating, there are three main estimates: conceptual, preliminary, and detailed estimate (Peterson, 2012). Conceptual and preliminary estimates are performed with no drawings or are based on a broad project outline. Traditional cost-estimation methods (unit price, cost per foot, or square foot) are used to prepare an estimate which is not possible for the conceptual estimate for a tunnel project because it is based on a broad project outline (Romero and Stolz, n.d). An estimate of this nature is subjective due to the scrutiny and quantification required by today's conscious public. In the traditional estimating, unknown factors can only be addressed after a detailed design and drawings have been prepared. In the proposed estimation approach, the conceptual estimate is calculated based on the physical independent variables of the tunnel.

To address the problem associated with traditional cost estimation methods, this study employed statistical analysis to develop a cost estimation function, termed tunnel cost estimation function (TCEF). The main emphasis of the present work is to develop suitable cost estimation functions that can be used to calculate cost estimates fairly accurately on the basis of historical data. The TCEF algorithm development process involves identifying parameters impacting tunnel construction cost and then using regression analysis to develop cost estimating functions. Developed cost functions are expected to produce realistic initial cost estimates for transportation tunnel projects. The algorithms developed are associated with subsurface conditions.

5.3. Related Literature

Cost estimation is a fundamental process of predicting expected costs and resources for a construction project to determine initial cost estimates for engineering and business decisions prior to bidding (Association for the Advancement of Cost Engineering [AACE] International, 1998 and Department of Energy [DOE], 2011, Rush and Roy, 2000, Membah and Asa, 2015). Cost estimates generally involve estimating quantities of materials and costs of labor, equipment, overhead, utilities, and other expenses.

At the feasibility phase, the factors may not be well-defined and may have considerable uncertainty associated with them. Estimating practice include planning, estimating, determining, performing, and controlling. For the purpose of this research, the term “cost estimating” is used interchangeably between planning and estimating. Designers need a cost estimation method which they can use to calculate estimates to evaluate potential tunnel project alternatives and contractors also need a tool to employ when bidding and budgeting, based on tunnel project parameters or variables. The parameters/variables refer to tunnel characteristics or attributes, such as diameter of tunnel, length of tunnel, and others. A number of methods have been proposed for use in calculating conceptual estimates during the feasibility phase (DOE, 2011). The parametric estimating method is one such method that could be used to calculate initial cost estimates during the early stages of a tunnel project. In parametric estimating, a relationship is established between the cost of similar past projects and the factors impacting tunnel cost. Parametric functions are developed by applying regression analysis techniques between the costs as a dependent variable and identified physical factors as independent variables based on historical project data (Dysert, 2008, International Society of Parametric Analysis [ISPA], 2008).

Parametric estimating is a method that was originally utilized by the Rand Corporation in the 1950's, termed Cost Estimation Relationship (Black, 1984; Krieg, 1979; Orczyk, 1990; ISPA, 2008). The method was used by the military to calculate the cost of an airplane acquisition based on attributes such as the speed, range, and altitude of the aircraft. It was developed to meet the needs of estimating new technology projects for government, but is now widely employed in many industries with long term project implementation periods and high capital investments (ISPA, 2008). In this scenario, risks and uncertainties increase the initial cost estimate of the project due to its long duration and must be addressed.

A parametric cost estimation function is developed by implementing a regression analysis (Kouskoulas and Koehn, 1974; Black, 1984; Karshenas, 1984; Hegazy and Ayed, 1998; Dysert, 2001; Trost and Oberlender, 2003; ISPA, 2008). Regression analysis is the best method of establishing a relationship between the tunnel variables and cost to develop the most appropriate algorithm of the model based on historical data (Black, 1984; Orczyk, 1990). Regression based methods have drawbacks, and as such, new research has developed novel alternative methods for example; neural network models but the method has suffered due to its opaqueness in the model development process (Moselhi et al., 1992; Hegazy and Ayed, 1998). According to Bode (1999), the neural networks method is still at the experimental stage due to its lack of applicable rules to set control variables and topologies.

A number of research studies on parametric models have focused on estimation of construction costs for building projects (Karshnas, 2005; Lowe et al., 2006; Sonmez, 2008; Ji et al., 2010); highway projects (Hegazy and Ayed, 1998; Al Tabtabai et al., 1999); and urban railway projects (Sonmez and Ontepeli, 2009; Gunduz and Ozturk, 2010). In a recent study, Fragkakis et al. (2011) developed a parametric model for conceptual cost estimation of concrete bridge foundations. Parametric cost estimation is most suitable for prediction, hypothesis testing, and modeling of relationships during the earliest stage of design or at any stage of the project. Parametric estimating is an important tool particularly during the bidding process, as it decreases the amount of time needed to develop a cost estimate. Dysert (2008) argues that the parametric cost estimation method is efficient, objective, consistent, flexible and defensible. Meyer and Burns (1999) observations that parametric approach when employed can avoid errors and omissions which are common when using traditional cost estimation methodologies in the early stages of the planning and design phrases.

Although parametric cost estimating is best employed in calculating preliminary or predesign cost estimates, it can also be used at any stage of a project for cost comparison or validation. Roy et al. (2000) used parametric cost estimation to predict the probability that the independent variable will change its values. In another study, Soutos and Lowe (2005) utilized a parametric model to identify potential cost variables. Furthermore, Oberlender and Trost (2001) elucidated that parametric cost estimates can be affected by changes in project scope, changes in design standards, incorrect unit cost/quantity assumptions, and unforeseen problems in implementation of the project. Yet with all the successes of this method, parametric estimating has inherent drawbacks such as: complexity of developing the function which requires statistical skills and historical data, cost estimate is an aggregate with no details, the difficulty of knowing whether present and past methods are the same, and parameters not included could become important (Membah and Asa, 2015). Despite its various disadvantages, parametric estimating provides adequate benefits as it is fast and effective, easy to justify, and repeatable and objective when the function scope is well-designed and applied.

In the parametric function development process, either parametric or nonparametric statistical procedures could be used to develop the function. Parametric statistical procedures are based on assumptions of a specific form of the distribution underlying the population from which the sample was taken; while on the other hand, nonparametric statistical tests require no or very limited assumptions about the distribution of the population from which the sample is drawn (McClave and Sincich, 2009). For parametric statistics, the problem comprises of estimating the parameters and testing hypotheses relating to them. Nonparametric statistics is not concerned with the techniques of estimating the parameters, but with specific hypotheses relating to the properties of the population. The major disadvantages of the nonparametric method are twofold. First, the method is considered to be less statistically robust compared to parametric methods because of its lack of information about the form of distribution function, and lastly results are often difficult to interpret compared to results of parametric tests.

5.4. Research Methodology

A theoretical parametric function is proposed that provides repeatability during model development. The parametric cost estimation function for transportation tunnel projects involves six primary steps: selection of cost drivers, data collection and normalization, data analysis, data transformation, model development, and testing of the function. The parametric cost estimation research methodology is depicted in Figure 5.1. The development process of the parametric cost estimation function is presented in the text that follows:

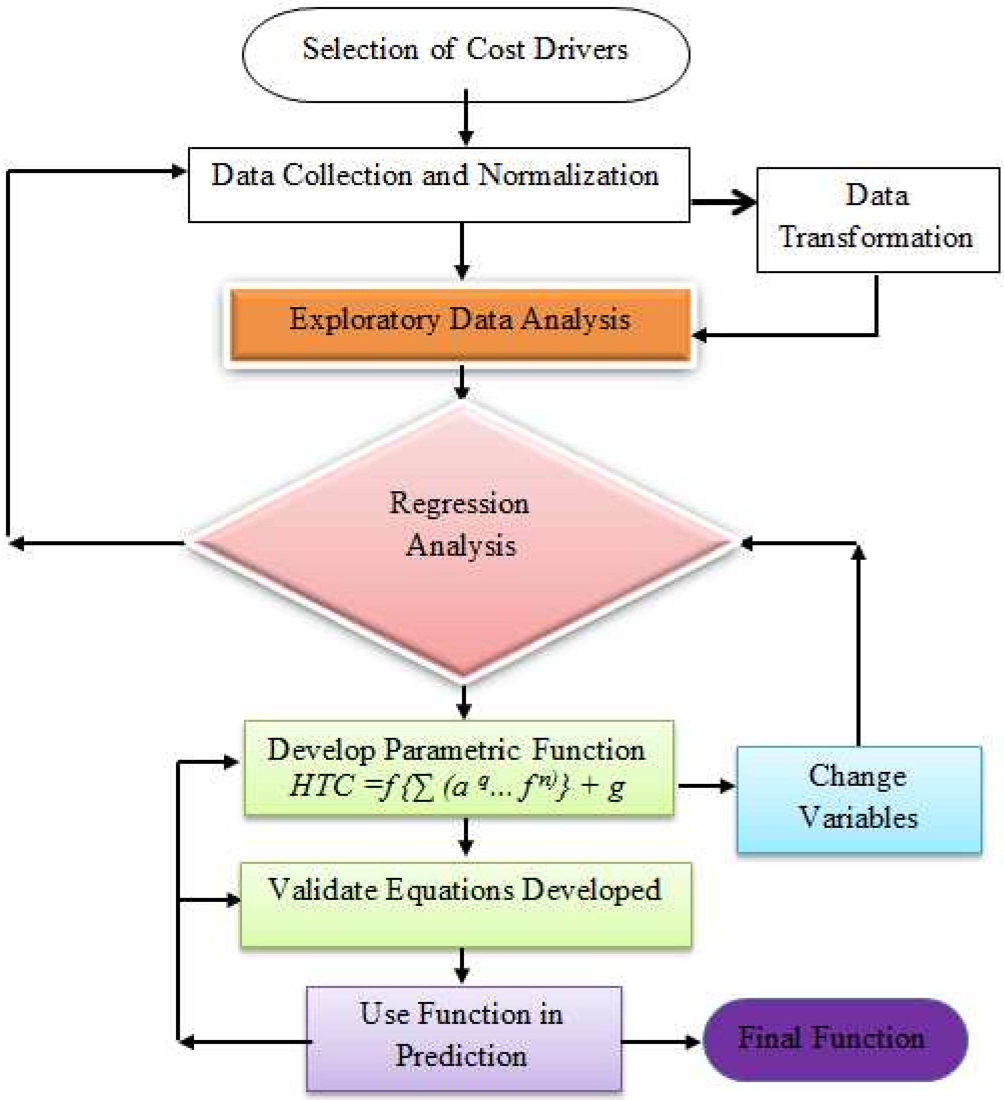

Figure 5.1. Proposed research methodology for parametric tunnel cost estimation function

5.5. Data Acquisition

The data from a database jointly maintained at Penn State University and New Mexico Tech, and the researchers (Sepehrmanesh, 2009) were used in this research. The original database was developed by utilizing data collected from project managers, professionals in academia, and construction industry players through a questionnaire survey. The tunnel project data collected were composed of attributes such as tunnel sizes, applications, locations, and ground conditions from North America. A database with a total of 272 tunnel projects was developed consisting of both transportation and service tunnel projects. The database compiled covered different tunnel applications and included metro, highways, water, waste water, storm water, railways, light rail, oil pipelines, and subways.

The data obtained were in a spreadsheet format for the different applications. However, a few gaps existed in the original data. Project start date and the depth of overburden for some tunnel projects were missing and were obtained from searching on their specific project websites. Any other information not gathered from the project website was collected through email correspondence.

After prescreening of the data, a new sub-database of transportation tunnel projects was compiled from the original dataset of 272 of tunneling projects comprising of both transportation and service tunnels. A new database was formed having 79 records relating to transportation tunnel projects out of the original 272 covering a span of 35 years. The tunnel projects covered in the study are from United States and Canada from 1979 to 2014. The tunnel projects comprised of highways, subways, and railways.

5.6. Selection of Cost Drivers Impacting Tunnel Cost

The first step in any parametric cost estimation function development is the selection of cost drivers related to the project (Ostwald, 2001, Dysert, 2008, and ISPA, 2008). The selection of cost drivers to be used in the function formulation was based on available tunnel project historical data and the significant parameters impacting tunnel construction cost that were identified through a variety of sources including published literature, technical manuals, and brainstorming sessions with academia/practitioners (Ostwald, 2001and ISPA, 2008). The cost drivers were selected through a systematic review (Membah and Asa, 2015). The discussion of the cost drivers in this section focuses on the factors used in the development of the parametric function.

Geological/ground conditions of a site have a pronounced effect on the final project cost estimates. Difficult geologic conditions could translate into higher construction costs, while on the other hand; favorable ground conditions can reduce construction costs. Transportation tunnels could be constructed in a wide range of possible ground conditions from soft soil to extremely hard rock (FHWA, 2009) combined with various *in-situ* stresses and hydrogeology. Kaiser and Kim (2008) report that a thorough study of the soil, rock mass strength, and field information needs to be carefully evaluated based on geological data collected to determine potential soil and rock behavior. The primary purpose of any tunnel investigation is to obtain the maximum amount of information on soil and rock characteristics, structural systems, strength, and groundwater conditions (Hoek, 1982). The data provides a rational means of correlating particular tunneling conditions, types of ground, and case histories to ensure that the best tunneling method is proposed for the anticipated soils and rock conditions as well as the hydrostatic pressures.

Tunnel construction involves materials handling (muck), and it is important that the physical properties of soil and rock be quantified for the success of tunnel project operations. In the case of tunnel projects bored through soils, it is important to consider: groundwater levels; consistency and strength of cohesive soils; composition, gradation, and density of cohesionless soils; presence of gravel, cobbles, and boulders; presence of cemented soils; and presence of contaminated soil or groundwater (FHWA, 2009). For the design of tunnel through hard rock geologic conditions, the following primary parameters are required: the rock mass strength, groundwater level, deformability, and permeability (Hoek and Palmieri, 1998). The tunnel parameters mentioned will influence the general engineering behavior of the ground and groundwater flow when carrying out construction processes.

It important that both laboratory and in-situ testing is performed on the soil and rock formations to determine the behavior of soil or rock surrounding the tunnel. Sabatini et al. (2002) lists and describes the tests required for rock and soil formations for tunnel construction work. The results obtained from laboratory and in-situ tests are used to characterize or classify the soil/rock material. The soil sample could be tested in accordance with the American Society for Testing and Materials (ASTM), 1984; the American Association of State Highways and Transportation Officials (AASHTO), FHWA, 2009; and others. Common soil classification systems used are Unified Soil Classification System, (USCS), AASHTO classification system, the OSHA (Occupational Safety and Health Administration) classification, the Engineering Stratigraphic Units, (ESU), and other systems. The USCS has three major divisions: coarse-grained, fine-grained and peat and each division are further subdivided into groups. The AASHTO system is grouped into granular, silt-clay, and organic, and further divided into subgroups. OSHA has three soil classification groups of A, B, and C.

On the other hand, the rock mass strength could be obtained by conducting compressive strength tests as described in the ASTM, 1984; the International Society for Rock Mechanics [ISRM], 1981; and FHWA, 2009.The characterization of the rock or soil material is particularly useful when performing feasibility studies and design for engineering projects (Ozturk and Nasuf, 2013). The rock materials classification is based on uniaxial compressive strength values, which are obtained from laboratory and *in-situ* tests performed. Bieniawski (1984) proposed several classes of rock materials as shown in Figure 2.

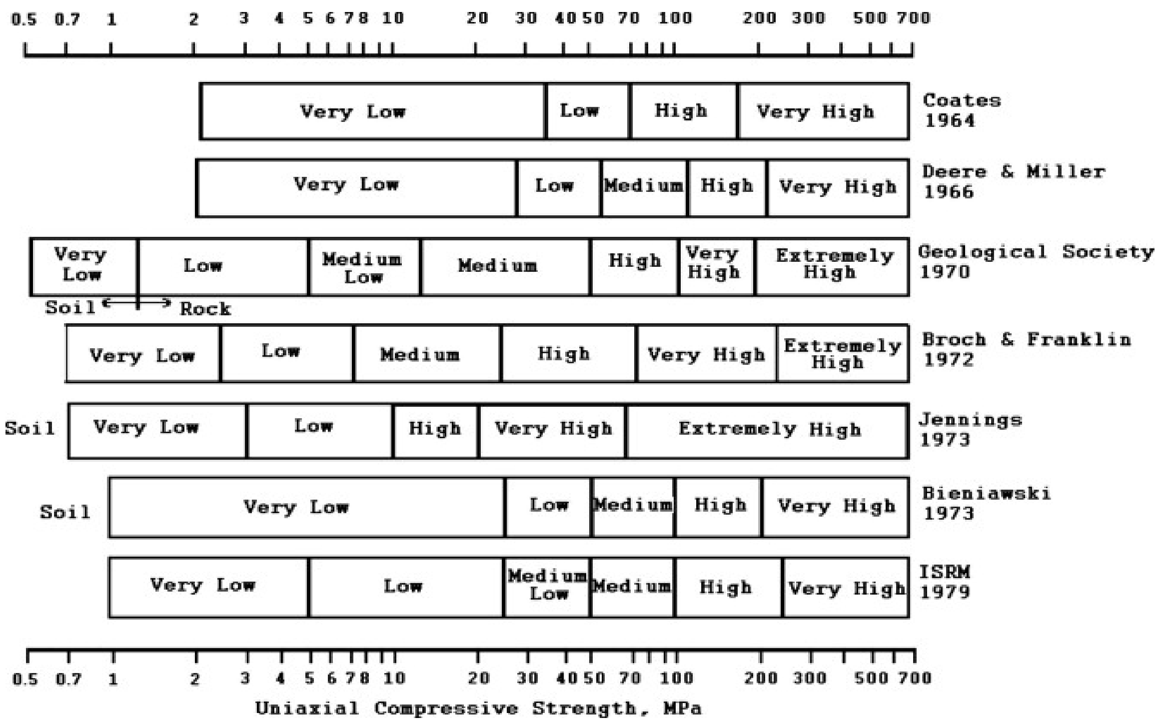

Figure 5.2. Classifications based on material strength (Bieniawski, 1984)

Figure 5.2 shows that the number of classes and class intervals are not consistent because they vary. The classification system proposed by Bieniawski (1984) is used to describe/quantify geological conditions in underground excavations. Rock mass classification systems form an integral part of empirical design considerations in underground projects. The classification systems group areas of similar geomechanical attributes, provide guidelines for stability performance, and select appropriate support requirements. The classification systems are primarily to quantify intrinsic properties of the rock material and investigate how external loading conditions act on a rock mass to influence its behavior. The most common rock mass classification systems used are (1) rock mass rating (RMR) developed by Bieniawski (1973), (2) rock mass quality designation (Q system) described by Barton et al. (1974), and (3) rock mass index (RMi) developed by Palmström (1995). These rock mass classifications apply quantitative estimation of rock mass quality to allow for adequate design considerations for rock support systems. The classification systems are applied during the early stages of design to compare alternative tunnel alignments.

The Rock Mass Rating (RMR) system also called the Geomechanics classification system was developed by Bieniawski in 1973 for characterizing rock material. Major revisions were done to the RMR system in 1974, 1975, 1976, and 1989. The RMR system is the primary tool used to estimate support requirements in underground projects. The RMR classification considers six parameters for the evaluation of a rock material. The following parameters are considered (Bieniawski, 1973; Hoek et al., 1995; Stille and Palmström, 2003): (a) uniaxial compressive strength of rock material; (b) rock quality designation; (c) spacing of discontinuities; (d) condition of discontinuities; (e) groundwater conditions; and (f) orientation of discontinuities.

The rock material is divided and grouped into a number of discrete regions, so that a particular region has similar characteristics (Bieniawski, 1973; Hoek et al., 1995). The information collected from the field is evaluated on the six parameters. The parameters are weighted differently based on their importance to describe the overall classification of a rock material, where a higher value range indicates a better rock mass condition. In the Geomechanics classification system, each parameter has a different weighting, and can only describe a rock material when they are considered together (Bieniawski, 1989). The RMR value obtained from the six parameters is used to classify the rock material from the pre-defined classes ranging from very low to very high. The RMR system is applicable to rock tunnels, rock foundations, and slopes.

The Q-System of rock mass classification was developed by Barton et al. of the Norwegian Geotechnical Institute (1974). The Q-system is based on a quantitative assessment of the rock mass quality expressed as a function of six parameters (Barton et al., 1974): rock quality designation (RQD); number of joint sets; roughness of the most unfavorable joint or discontinuity; degree of alteration of filling along the weakest joint; water inflow, and stress condition. The Q value is estimated by employing equation 5.1 (Barton et al., 1974):

$$Q = \frac{RQD}{J_n} x \frac{J_r}{J_a} x \frac{J_w}{SRF} \tag{5.1}$$

where RQD is rock quality designation, J_n is joint set number, J_r is joint roughness number, J_a is joint alteration number, J_w is the water reduction number, and SRF is the stress reduction number. The first part of the expression RQD/J_n represents the block size, the second part J_r/J_a reflects the inter-block shear strength, and lastly J_w/SRF represents the effective stress conditions.

The Rock Quality Designation (RQD) was proposed by Deere in 1964. The RQD is the modified core recovery index defined as the total length of intact core greater than 4 inches long, and divided by the total length of the core run. The resulting value is presented in the form of a percentage. The RQD is calculated over individual core runs, intact length of core considering only core broken by joints, or other naturally occurring discontinuities.

Rock Mass Index (RMi) was proposed by Palmström in 1995. The RMi is composed of four input parameters: the size of the block delineated by joints (block volume); the strength of the block material (uniaxial compressive strength); the shear strength of the block faces (friction angle); and the size and determination of the joints (length and continuity). The RMi input parameters are calculated using equation 5.2, whose value is in units of pressure (Palmström, 1995, Stille and Palmström, 2003):

$$RMi = \sigma_c * JP \tag{5.2}$$

Where σ_c is the uniaxial compressive strength of the intact rock mass, and *JP* is the jointing parameter expressed in terms of the block size and the condition of its faces represented by their frictional properties and the size of their joints. The uniaxial compressive strength of the rock material is an important paramter when developing the RMi and the overall classifiation of the rock material.

The current classification system proposed by Bieniawski (1984) only classifies soil into a single group. In this research study, rock and soil formation are classified into two groups; hard rock and soft rock because the sample obtained was not large enough to be divided into smaller groups. The criteria for differentiating between hard and soft rock is derived from the stand-up time. Hard rock is a natural substance composed of minerals that can be self-supporting for some time (stand-up) after initial excavation of the tunnel. Nguyen et al. (2014) defines stand-up time as the amount of time a tunnel will support itself without any added support structures. Lauffer (1958) proposed that for any given ground condition the stand-up time decreased with increasing length of the active span. Lauffer's work has since been modified to take into account rock mass classification such as Q-system and RMR system. Barton et al. (1975) proposed a relationship between stand-up and rock classification with unsupported. Hard rock in this work is therefore proposed as the rock defined by medium strength rock and above (Table 5.1). Also, the proposed soft rock classification is defined by low strength rock, including soil.

Table 5.1 classifies ground classification into hard and soft rock groups on the basis of physical properties of soil and rock mass. It also factors the stand-up time as aforementioned.

Table 5.1. Proposed ground classification in relation to tunnel design.

Classification	Uniaxial compressive strength (MPa)	Ground types
Soft Rock		
Type C soil	Less 0.048	Granular soils including: gravel, sand, and loamy sand.
Type B soil	0.048 to 0.144	Granular cohesionless soils including: angular gravel, silt, silt loam, sandy loam, and dry unstable rock.
Type A soil	Above 0.144	Cohesive soils including: clay, silty, sandy clay, and clay loam
Very low strength rock (Very Low)	Up to 25	Low strength rocks including shales, Cretaceous Chalk, Triassic (Keuper) Marl and Jurassic rock formations. Material crumbles under firm blow with a sharp end of a geological pick and can be peeled off with a knife.
Low strength rock (Low)	25 - 50	Low strength rocks including shales, Cretaceous Chalk, Triassic (Keuper) Marl and Jurassic rock formations. Material can be scraped and peeled with a knife.
Hard Rock		
Medium strength rock (Medium)	50-100	Many Triassic and Permian rock formations, sandstones and medium strength Carboniferous Coal Measures. Specimen can be broken with the hammer end of a geological pick with a single firm blow.
High strength rock (High)	100 - 200	The hard Carboniferous and older rocks, limestone and harder rocks. Hand-held specimen breaks with hammer end of pick under more than one blow.
Very high strength rock (Very High)	Above 200	The hard Carboniferous and older rocks, limestone and harder rocks. Specimen requires many blows with geological pick to break through intact material.

Environmental requirements are defined as requirements intended to address potential issues and impacts related to the construction and operation of a tunnel project to its surrounding area and affected communities, and the environment within the tunnel alignment (FHWA, 2009).The environmental issues that might be effected by a transportation tunnel project include degradation of habitats, fragmentation of wildlife and habitats, disturbance of fauna, noise, vibrations, pollution, air quality and others (van Geldermalsen, 2004, FHWA, 2009). Environmental issues may occur during all the phases of the construction processes. During the feasibility phase, environmental issues should be identified, examined, and appropriately addressed to provide adequate information to the stakeholders to assist them in understanding the consequences of their decisions (Flyvbjerg et al., 2003, FHWA, 2009). Type of ground and duration of project implementation include methods and procedures that might impact the quality of the environment, natural resources, and health of the community along the alignment, and requires contractors to comply with certain standards and regulations (Schexnayder et al., 2003, FHWA, 2009). Complying with the standards and regulations might affect the number of days the contractors will take to complete the tunnel project. The duration of the tunnel project is significant due to the inherent costs required to accelerate a construction schedule, and would have a direct bearing on the bid price offered by the contractors.

Excavation method(s) is/are selected by considering tunnel size, function, cost, schedule, geologic and geotechnical conditions, and possible impacts to adjacent structures, if any. Potential feasible construction methods that could be used to construct the tunnel range from cut and cover for shallow depth, drill and blast for tunnels in hard rock, to Tunnel Boring Machine (TBM) and Sequential Excavation Method (SEM) approaches for tunnel excavation at greater depths (FHWA, 2009). A combination of techniques could be employed as well. Each method or combinations of methods are suitable for particular geological conditions (U.S. Army Corps of Engineers [USACE], 1985, FHWA, 2009). Each method has advantages and disadvantages, and its suitability is dependent on ground conditions and the environment. Any method adopted will cause ground movements, and the ground movements will be affected by tunnel depth, tunnel diameter, geological conditions, and the quality of construction. It is important that the cost and disruption of such measures be balanced with the cost and disruption of alternative tunneling methods.

Cut and cover- is a method of tunnel construction that employs the use of support systems followed by the main excavation. Support systems to provide earth support include: slurry walls, bored pile walls, and sheet pile walls. It is commonly used for construction of tunnels that are not very deep (FHWA, 2009). The method can accommodate any change in tunnel width and irregular shapes. This method is used for overlapping works. The integral parts of this method are trench excavation, tunnel construction, and soil covering of the tunnel (FHWA, 2009). The traditional cut and cover method requires the ground to be open during the entire period of construction and the main excavation takes place with full surface access.

There are many advantages of the cut and cover tunnel construction method. It is less expensive than underground tunneling methods for shorter lengths and relatively shallow depths because of simpler excavation methods, and requires shorter overall construction duration for shorter lengths of tunnel (FHWA, 2009). Additionally, underground obstructions can usually be handled without excessive increases in cost and schedule, it offers flexibility in terms of horizontal alignments if other constraints allow (e.g. building foundations) and in tunnel cross sections, and construction in close proximity to existing buildings is achievable with good control of ground movements (FHWA, 2009). The disadvantages of the method are: major construction phase impacts and disruption due to open excavation, including lane closures, temporary relocation of building access points, and diversion of traffic; impacts will be experienced along the full length of the tunnel due to open excavation; less economical for longer lengths of tunnel; major right-of-way and property requirements for excavation; and major utility diversions are likely to be required (FHWA, 2009).

Drill and blast is a cyclic operation involving, drill, blast, muck, and installation of primary support. The tunnel construction method involves the use of explosives (FHWA, 2009).

First, drilling rigs make a pattern of small holes on the proposed surface to a predesigned depth for blasting, they are loaded with explosives (timed and delay detonators), and then explosives are detonated thus creating an opening in rock. Blasted and broken rock is removed and the rock surface supported (FHWA, 2009). The same procedure is repeated several times until the desired opening in rock is achieved. A final lining is placed after the entire tunnel has been excavated and supported.

The advantages of drill and blast tunnel construction method are: potential environmental impacts in terms of noise and dust; compared with the cut-and-cover technique, quantity of cut and disposal materials generated would be much reduced; compared with the cut-and-cover technique, disturbance to traffic and associated environmental impacts would be much reduced; and blasting would significantly reduce the duration of vibration, though the vibration level would be higher compared with bored tunneling (FHWA, 2009). The main disadvantage of the tunnel construction method is the potential hazard associated with the establishment of a temporary magazine site for overnight storage of explosives, which can be addressed by avoiding populated areas in the site selection process (FHWA, 2009).

Tunneling boring machine is a method of tunnel construction that involves procuring a custom-made piece of construction equipment. The TBM is equipped with a cutter head designed to suit the geological conditions anticipated to be encountered during the tunnel excavation (USACE, 1985, FHWA, 2009). The cutting tools mine the ground and the resultant excavated material is removed behind the cutter head. The TBMs are categorized into open-face and closed-face shielded machines (FHWA, 2009).

The major advantages of the TBM bored tunnel construction method are: efficient for longer tunnels as economies of scale are realized for the capital investment in the TBM and precast concrete lining assembly; minimizes surface disruption as the majority of the construction work takes place below ground (with the exception of portal and station locations); limits the material handling (supply and removal) to discrete locations rather than the entire length of the tunnel; and minimizes the need for utility diversions (FHWA, 2009). The major disadvantages of the TBM bored tunnel construction method are: more expensive for shorter lengths of tunnel owing to the capital investment in the TBM and the precast concrete lining assembly; dealing with underground obstructions can potentially be costly and time-consuming; shallow vertical tunnel alignments may result in ground movements that pose potential for structural damage to nearby buildings, thereby requiring protective works; horizontal tunnel alignments are potentially limited by the capability of the TBM; tunnel material handling will be concentrated in discrete locations; and changes in tunnel diameter are not achievable without other construction methods (FHWA, 2009).

Sequential excavation method- is a method of tunnel construction where the proposed tunnel is divided into segments, and each segment excavated sequentially with supports USACE, 1985, FHWA, 2009). An initial lining of sprayed concrete provides immediate support and a permanent lining is then placed based on the designed support system. In general, a waterproof membrane is installed between the primary and permanent linings. Excavation machines, such as road-headers and backhoes could be used for tunnel excavation (FHWA, 2009). Ground for excavation must be dry before the excavation by SEM as well ground dewatering. After excavating the tunnel, support sections are put in place to support the sides. Support systems are defined as procedures and materials used to improve and maintain the load bearing capacity of rock or soil near the boundary of an underground excavation; including shotcrete, steel mesh, timbering, steel concrete lining, or a combination of two or more methods (Hoek and Wood, 1987).

The major advantages of the SEM tunnel construction are: flexibility in terms of horizontal alignments if other constraints allow and in tunnel cross section. The tunnel cross section does not need to be circular as for a TBM bored tunnel, and this can lead to optimization of the tunnel cross section and reduced costs; generally shorter overall construction duration for shorter lengths of tunnel; underground obstructions can usually be handled without excessive increases in cost and schedule; minimizes surface disruption as the majority of the construction work takes place below ground; potential to limit the material handling to discrete locations rather than the entire length of the tunnel if suitable shaft access sites can be found; and minimizes the need for utility diversions (FHWA, 2009). The major disadvantages of this tunnel construction method are: significant ground treatment may be required to stabilize the excavation during tunneling, as the tunnel is not sealed off from the ground water pressure as it is with a pressurized face TBM driven tunnel; less economical for longer lengths of tunnel; and shallow vertical tunnel alignments may result in ground movements that pose potential for structural damage to nearby buildings, thereby requiring protective works (FHWA, 2009).

In the discussion of cost drivers, each factor is discussed separately. The influence among the factors is not discussed, for example, technological innovation, which is the application of new methods termed “state-of-the-art” consisting of new equipment and/or methods of construction that have limited prior application (Schexnayder et al., 2003). The other factors are political influences and restrictions where requirements are placed on the proposed project by communities or state and federal agencies (FHWA, 2009). These, and other factors, make the development of an accurate estimating method difficult, due to the possibility of the interplay of these variables which is not addressed. Generally, tunnel projects in urban areas are greatly affected by these requirements and might include types of construction methods that can be employed for the work and particular hours allowed for work operations (FHWA, 2009).

5.7. Data Pre-Processing

Once the data for the 79 tunnel projects were available, data pre-processing was undertaken. Data were normalized for year of construction and location to make it suitable for statistical analysis. In this research, data adjustments involved time and location and were performed by converting tunnel costs into constant US dollars. Cost indices are developed to capture the trends in the cost of an item from one location point in time to another. The index is used to adjust the cost to a common base year. The indices are published monthly by Engineering News Record (ENR) for both the Construction Cost Index (CCI) and the Building Cost Index (BCI) since 1921 (Westney, 1997; Grogan, 2003), and they have been used to predict cost trends in the construction sector (Wilmot and Cheng, 2003).The CCI and BCI can be applied to construction materials and services cost to adjust for location and potential escalation costs to the base year under consideration. The CCI can be applied where labor cost is the main proportion of the main cost, while BCI is applicable to surface structures such as buildings (ENR, 2015). The difference between the two is that CCI take into account a large portion of labor compared to BCI. The CCI is computed from 200 hours of common labor compared to 66.38 hours for BCI (ENR, 2015).

In the present work, the CCI was applied to the tunnel project's year of construction costs to account for time by city to adjust them to the base year due to the high cost of labor of the project costs associated with such projects (March, 2014). The ENR (2015) defines construction cost index as the weighted aggregate of the prices of constant quantities of labor, structural steel, Portland cement, lumber, and equipment in 20 cities in the USA and Canada. The CCI is commonly used by cost estimators, investment planners, and financial institutions to estimate construction costs, prepare budgets during the planning phase, and undertake cost control during the construction phase (Touran and Lopez, 2006; Ashuri and Lu, 2010; Xu and Moon, 2013). It measures cost trends in the construction industry (Wilmot and Cheng, 2003; Touran and Lopez, 2006). The final tunnel project cost was obtained by multiplying the total tunnel project cost by the March, 2014 index, and then dividing by the respective construction cost index of the prior year, the only way project costs can be compared and rightly analyzed (Equation 5.3).

$$Cost_{now} = Cost_{then} * \left(\frac{Cost\ \ Index_{now}}{Cost\ \ Index_{then}} \right) \tag{5.3}$$

For the location factor, equation 5.4 is used.

$$Cost_{at\ A} = Cost_{at\ B} * \left(\frac{Cost\ \ Index_{at\ A}}{Cost\ \ Index_{at\ B}} \right) \tag{5.4}$$

5.8. Data Analysis

The fourth step in the function development process is exploration or exploratory data analysis. According to Levine and Roos (2002), data analysis is the process of systematically applying statistical techniques to describe facts, detect patterns, develop explanations, and test hypotheses. Data exploration is important in function development. Analysis of data helps to verify whether a hypothesis is valid, reproducible, and unquestionable. A number of methods are employed in data analysis such as classical analysis and Bayesian analysis.

The exploratory data analysis method involves data examination using statistical techniques to graphically display and interpret data (Tukey, 1977). Exploratory data analysis is used to understand the data by providing trends, skewedness, and distribution. The outputs of statistical analysis are histograms, scatter plots, cross plots, and descriptive statistics (Shelly, 1996). The results of the exploratory data analysis help in making logical choices and procedures when performing regression analysis to determine the effects of primary parameters on the cost of transportation tunnel projects. The exploratory data analyses of the primary variables for hard and soft rock are presented in Table 5.2.

Table 5.2. Exploratory data analysis of primary variables.

Parameter attributes	Statistics	Hard rock	Soft rock
Overburden depth (m)	Minimum	0.00	8.00
	Maximum	38.00	57.00
	Mean	15.06	20.79
Length of Tunnel (km)	Minimum	0.96	1.00
	Maximum	29.10	28.00
	Mean	4.36	7.11
Diameter of tunnel (m)	Minimum	3.25	3.80
	Maximum	16.25	17.20
	Mean	7.58	7.23
Tunnel project cost ($millions)	Minimum	11.20	34
	Maximum	733.50	9090
	Mean	264.20	808

On the basis of exploratory data analysis results on the transportation tunnel data set, it is evident that most of the parameters investigated were skewed. In general, a skewed distribution is an indication of high deviations from normality. As such, it is necessary to perform data transformation on the data sets prior to performing regression analysis. Data transformation is a method of modifying variables to satisfy statistical assumptions or to improve the relationship between the variables (Hair et al. 1998). In this study, the procedure proposed by Box and Cox (1964) was used to transform the nonnormal data into a normal distribution. The algorithm used in performing data transformation reduces the skewedness and kurtosis present in the original dataset (Hamilton, 1992). The transformations used in this study are primarily based on exploratory data analysis. The Box-Cox procedure was chosen to identify the distribution that fits the data. The procedure selects a transformation to remediate deviations from assumptions of regression analysis. For this research, all statistical analyses were performed using the statistical package, Minitab version 17. Minitab provides different options of selecting a method for determining lambda. Common transformations include natural log ($\lambda = 0$), square root ($\lambda = 0.5$), or by choosing any value between -5 and 5 for lambda. For practicality, a λ within the range of -2 and 2 is chosen (Minitab, 2013). The Box-Cox procedure can only be applied with nonnegative data.

5.9. Regression Models

After exploratory data analysis and data transformations were performed, the next stage was to run regression analysis against the data to determine the best algorithms for the parametric function. The function could be developed using either parametric or nonparametric statistical procedures on the basis of the data available. The parametric functions when well-designed and applied can improve the accuracy of project cost estimates, reduce overruns of budgets and schedules, reduce project proposal costs, and enable consultants and stakeholders to consider different alternatives. In parametric cost estimating, regression analysis is used to fit a relationship to the dependent variable (cost), which is uncontrolled, and one or more independent variables, which are measured and controlled based on project attributes. Regression analysis is a statistical process for investigating the relationships between variables (McClave and Sincich, 2009). In regression analysis, different techniques are used to investigate the relationships including linear regression, nonlinear regression, and others.

In the present work, the natural log was utilized in the development of TCEF algorithm and a λ within the range of -2 and 2. Multivariable analysis was used to derive a parametric function or equation to predict the cost estimate of a transportation tunnel project. During the function development process, different statistical parameters were used to evaluate the significance of the variables. The function developed could then be used to calculate initial cost estimates, and at the same time employed in cost prediction related to variable changes. The tunnel cost function was hypothesized to be of the following general form (equation 5.5):

$$TCEF = \beta_0 + \sum_{i=1}^{n} \beta i * xi + e_i \qquad (5.5)$$

where TCEF is the expected tunnel cost estimate, the dependent variable; β_0 is a constant; n is the number of independent variables; xi are the independent variables; and *e* is the residual. The primary assumptions of regression analysis are: (1) $E(e_i) = 0$ for all $i = 1, 2, \ldots$ n; which implies that the function is linear and all variations in the dependent variable are random and unpredictable. Therefore, the expected value of the independent variable is given by equation 5.6.

$$TCEF = \beta_0 + \sum_{i=1}^{n} \beta i * xi \qquad (5.6)$$

(2) $Var(e_i) = \sigma^2$ for all $i = 1, 2, \ldots$ n; the implication of the assumption being that the variance of each error is the same; and (3) $Cov(e_i\, e_j) = 0$ for all $i \neq j$, the error term is uncorrelated, which implies that the dependent variables are uncorrelated. The least square estimate was used to find the coefficient β estimates such that the sum of square of deviation of the number of dependent variable (Tunnel cost estimate) from the modeled values was minimized. On the basis of a systematic literature review, the ground conditions category was identified as the leading cost driver in transportation tunnel projects. Cost analyses and functions development were performed on the following conditions: geological site location (soft or hard rock) and the methods used in tunnel excavation (drill and blast, tunnel boring machine [TBM], cut and cover, and mixed methods). Geological condition is a fundamental source of risk and uncertainty in underground construction facilities.

5.10. Geological Condition

The dataset was divided into two samples, hard rock and soft rock because the sample obtained was not large enough to be divided into smaller groups. Both samples of hard rock and soft rock contained 38 and 41 projects representing 48% and 52% of the dataset, respectively. Data for each project consisted of duration construction, method of tunnel excavation, depth of overburden, soil condition, length of tunnel, diameter of tunnel, and total tunnel project cost.

The histogram for the entire dataset is shown in Figure 5.3. Figure 5.3 shows that overburden, length of tunnel, diameter of tunnel and tunnel total cost is skewed to the left. The descriptive statistics for the parameters confirms this as shown in Table 5.3.

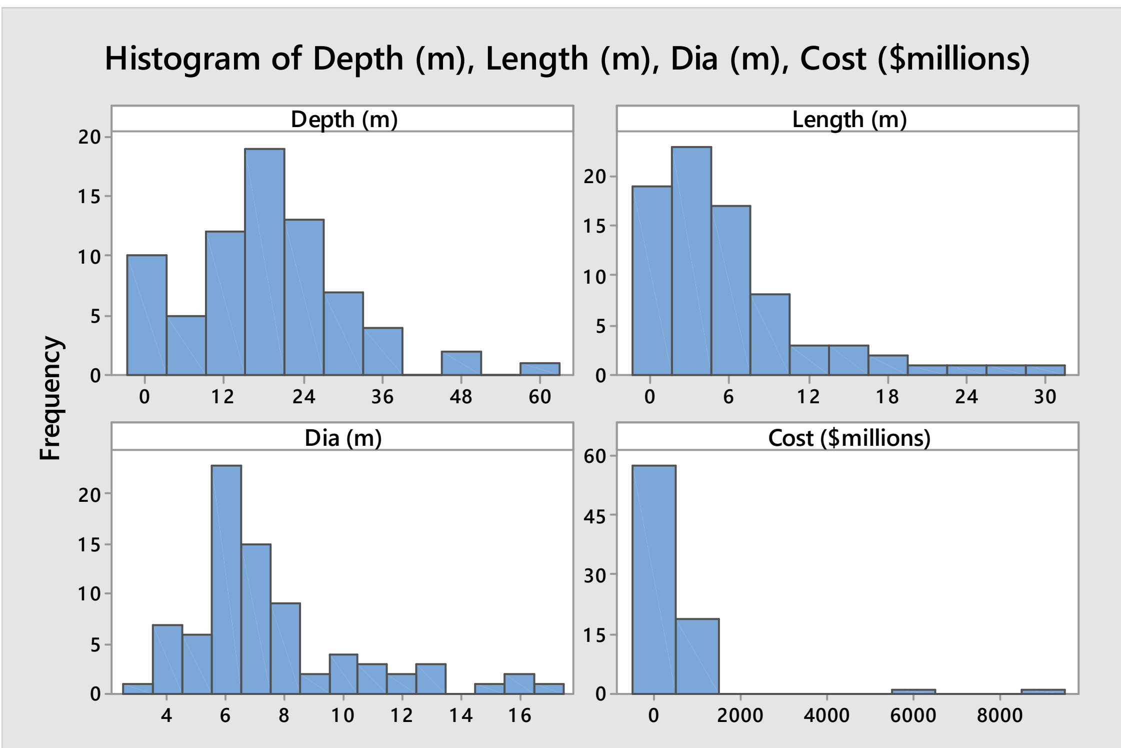

Figure 5.3. Histogram depiction of tunnel variables for the entire dataset

Table 5.3. Descriptive statistics of depth, length, diameter, and cost for entire dataset.

Variable	Mean	St. Dev	Minimum	Median	Maximum	Skewedness	Kurtosis
Depth (m)	18.03	12.05	0.00	17.00	57.00	0.70	0.97
Length (m)	5.818	6.091	0.960	4.000	29.100	2.05	4.43
Diameter (m)	7.500	2.996	3.250	6.560	17.200	1.47	2.09
Cost($millions)	546	1210	11	246	9090	5.83	37.08

The study was not confined to identification and description of cost drivers impacting tunnel cost, but was also for use in developing tunnel cost function. For this reason, independent variables must be well established with a clear definition to avoid ambiguity and inconsistency, have quantifiable values, and lastly cost values must be readily available with realistic accuracy. The following independent variables were adopted in this research: depth of overburden, length of tunnel, and diameter of tunnel as physical independent variables. The independent variables were considered both individually and in a group when performing analyses. Depth of overburden is the depth at which the tunnel is likely to be located below the ground surface; while length is the total length of the proposed tunnel alignment. Conceptual cost estimate is directly proportional to the total tunnel length. The selected tunnel diameter or cross-section must maximize the usable space. For transportation tunnels, the diameter adopted should allow for the passage of trucks and all other traffic, at the same time maintaining the required roadway standards. It also needs to accommodate spaces for ventilation, signage, walkway access to cross passages, and other facilities required for the tunnel system (FHWA, 2009). For railway tunnels, accommodation of some facilities might not be required. After selecting the cost variables, a preliminary data analysis was performed to understand the impact of the independent variables on the cost of transportation tunnel projects.

Equations were fitted to the two datasets of hard and soft rock and the results are presented in Figure 5.4. Figure 5.4 shows a scatter plot of cost versus diameter for both soft and hard rock ground conditions for transportation tunnel projects. For the soft ground conditions, a curvilinear curve and a power curve were fitted for the hard rock and soft rock datasets, respectively. A summary of the analyses for both hard and soft ground conditions is given in Table 5.4.

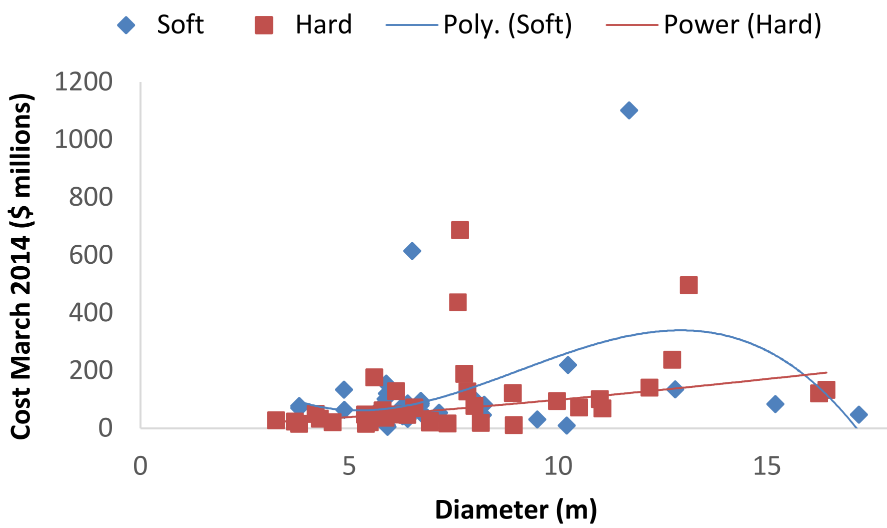

Figure 5.4. Cost vs. diameter for soft and hard rock ground conditions

Table 5.4. Summary of fitted curves for both soft and hard rock ground conditions.

Ground condition	Data Points	R^2	Equation fitted to the curve
Hard rock	38	0.2726	Cost = $4.3758D^{1.3527}$
Soft ground	41	0.1656	Cost = $-1.212D^3 + 33.00D^2 - 245.48D + 616.02$

5.10.1. Cost analyses and functions development for the hard rock tunnel data

In the function development, equation 5 is used to model the tunnel cost function. A representation of depth, length, diameter, and total cost in the form of histograms for hard rock dataset are shown in Figure 5.5. The TCEF algorithm developed from the regression analysis of the independent variables had a p-value of 0.517 corresponding to the variable overburden in the regression model. The p-value for overburden was the highest, and the variable was eliminated from the function.

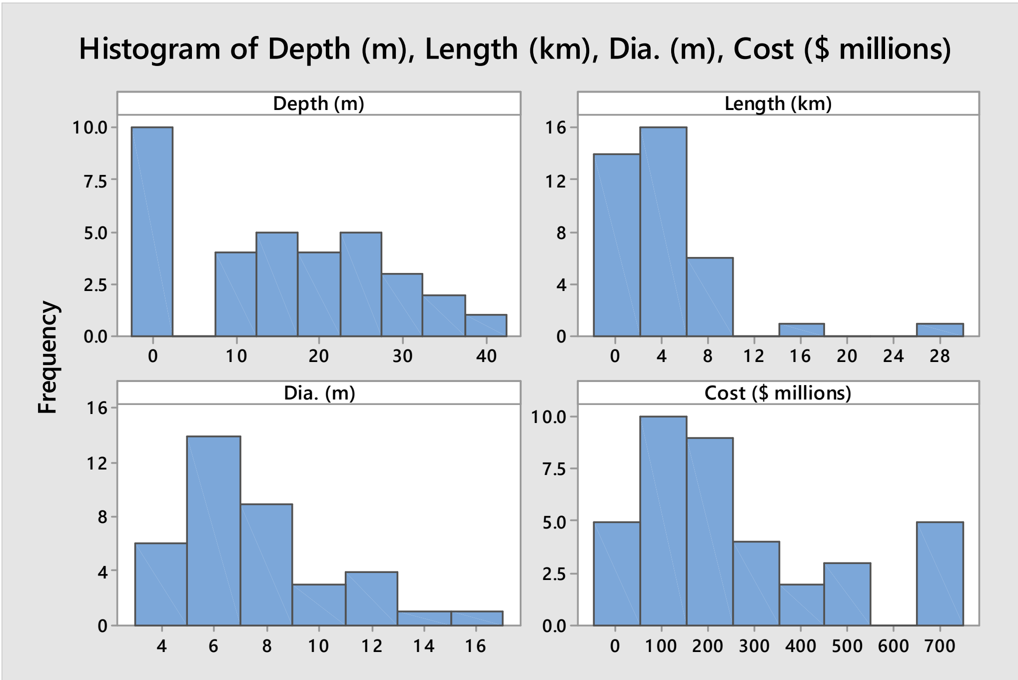

Figure 5.5. Histogram of depth, length, diameter and cost

In the second step, after eliminating tunnel overburden, the p-value was 0.337, the highest related to the variable diameter^2. From the results of the second regression analysis, it was clear the parameter diameter^2 did not contribute significantly to the function and thus it was eliminated from the model. Subsequently, the duration of the tunnel project was eliminated in the third regression analysis having a corresponding p-value of 0.372. The fourth regression analysis included the variables of length of tunnel, and diameter of tunnel. Both variables contributed significantly to the function as the largest p-value was 0.003. The new function for the expected TCEF is given by equation 5.7. The corresponding coefficients obtained for each independent value and their corresponding p-values and analysis of variance of the function are shown in Tables 5.5 and 5.6, respectively.

$$TCEF = e\hat{}\,(3.344 + 0.1601\ Le + 0.1536\ Di) \qquad (5.7)$$

S = 0.919527　　R-sq = 34.63%　　R-sq (adj) = 30.90%

Table 5.5. Variables with the p-values for hard rock.

Variable	Coefficient	SE Coefficient	T-value	P-value
Constant	3.344	0.457	7.31	0.000
Length of tunnel	0.1601	0.0489	3.27	0.002
Diameter of tunnel	0.1536	0.0472	3.26	0.003

Table 5.6. Analysis of variance of tunnel cost for the hard rock dataset.

Source	DF	SS	MS	F	P
Regression	2	15.679	7.8395	9.27	0.001
Residual Error	35	29.594	0.8455		
Total	37	45.273			

In the new function, tunnel cost is dependent on length and diameter of the tunnel. There is evidence of the robustness of the final equation as explained by the low p-values of length and diameter at 0.002 and 0.003 respectively. Also, standard error of the function was low at 0.92% compared to 5% of the confidence interval.

5.10.2. Regression analysis of soft rock tunnel data

For the soft rock dataset, the general equation 4 was used to develop the tunnel cost estimation function. In the regression analysis, the same procedure used to develop the TCEF algorithm for the hard rock data was adopted. A diagrammatic representation of depth, length, diameter, and total cost in the form of histograms for the soft rock dataset are shown in Figure 5.6. In the first step of the regression analysis, the duration of tunnel project variable had the largest p-vale of 0.868, and thus tunnel diameter variable was eliminated from the function. In the second regression analysis, the depth of overburden had a corresponding p-value of 0.400.

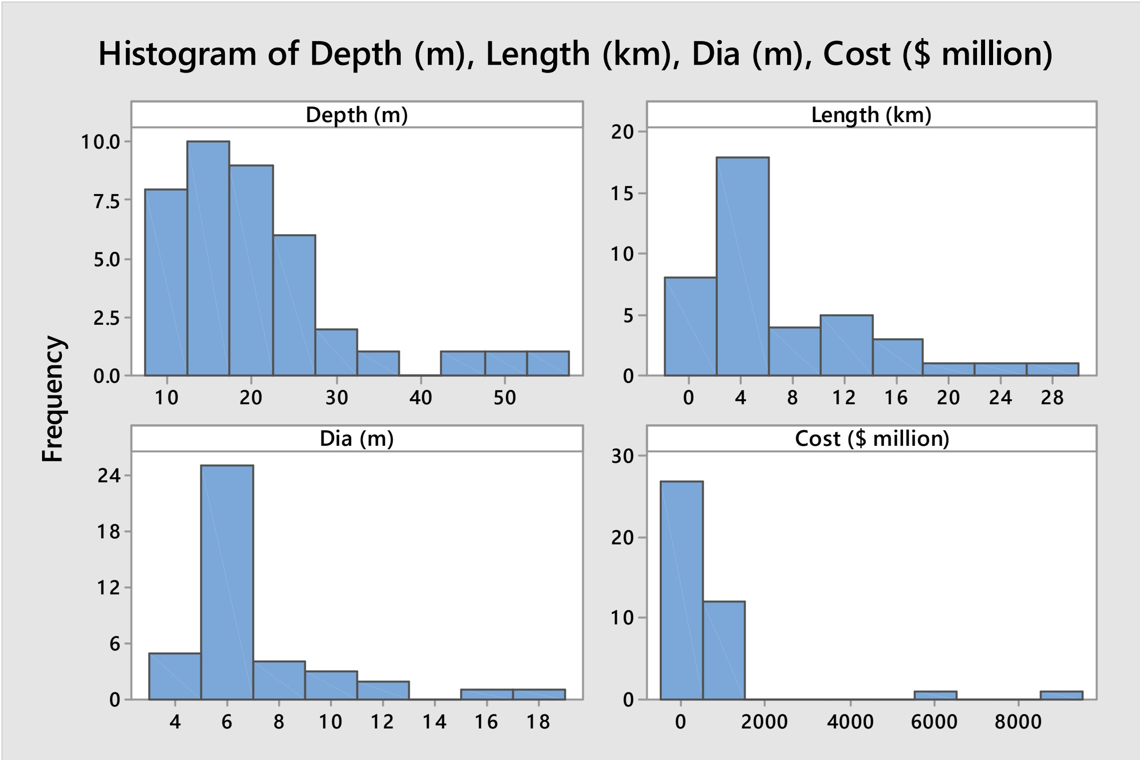

Figure 5.6. Histograms of depth, length, diameter and cost

The results revealed that the overburden depth did not contribute significantly to the function and was thus eliminated. The fourth regression analysis included the variables of length of tunnel, diameter of tunnel, and tunnel diameter^2. The three variables contributed significantly to the function as the largest p-value was 0.002. The new function for the expected TCEF is given by equation 5.8. The corresponding coefficients obtained for each independent value and their corresponding p-values and analysis of variance of the function are shown in Tables 5.7 and 5.7, respectively. The t-statistics show that the independent variables are good predictors of cost because of the low p-values less than 0.05 the confidence interval.

$$TCEF = e\hat{}(0.087\,Le + 1.1904\,Di - 0.0591\,Di^2) \quad (5.8)$$

S = 1.108 R-sq = 96.70% R-sq (adj) = 96.44%

Table 5.7. Variables with the p-values for soft rock.

Variable	Coefficient	SE Coefficient	T-value	P-value
Length of tunnel	0.087	0.0269	3.24	0.002
Diameter of tunnel	1.1904	0.0785	15.16	0.000
Diameter of tunnel squared	-0.05917	0.00640	-9.25	0.000

Table 5.8. Analysis of variance of tunnel cost for the soft rock dataset.

Source	DF	SS	MS	F	P
Regression	3	1366.08	455.362	370.95	0.000
Residual Error	38	46.65	1.228		
Total	41	1412.73			

In the new function, tunnel cost estimation is dependent on length of tunnel, LT, diameter of the tunnel, TD, and the square of diameters, TD^2. There is evidence of the robustness of the final equation as explained by the low p-values of the variables investigated of less than 0.001. Also, the standard error of the function was low at 1.108% compared to 5% of the confidence interval.

5.10.3. Cost analyses and functions development for tunnel excavation methods

Equations were fitted to the tunnel excavation method datasets (TBM, blast and drill, cut and cover, and mixed methods) and the results are presented in Figure 5.7. Figure 5.7 shows a scatter plot of cost versus diameter for the tunnel excavation methods considered for transportation tunnel projects. For the four tunnel excavation methods, different curvilinear curves were fitted to the datasets (Table 5.9). The analyses of the different tunnel excavation methods show that the correlations are low except for the drill and blast method (84%). A summary of the analyses for the four excavation methods investigated is given in Table 5.9.

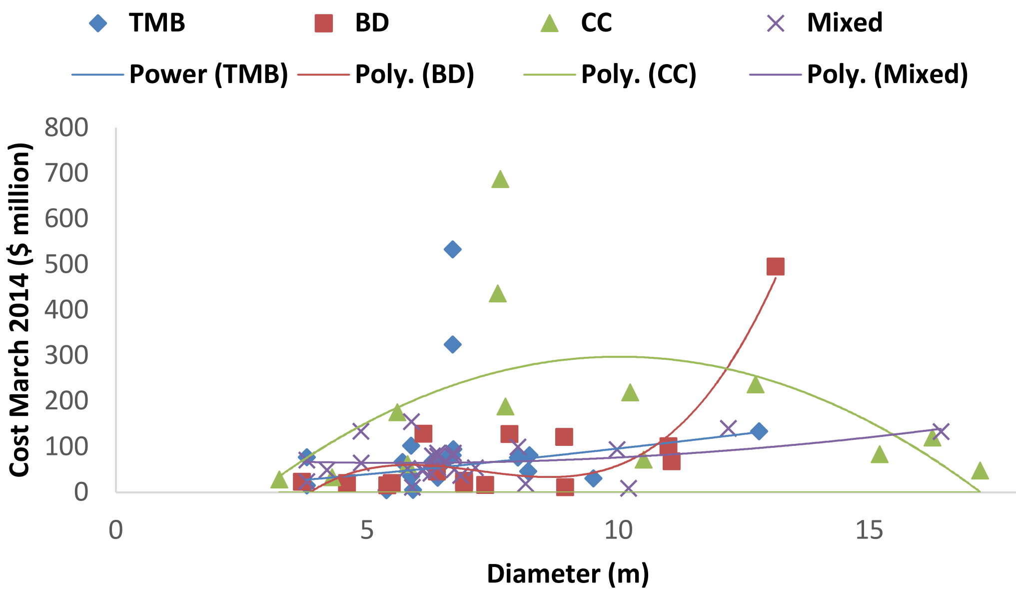

Figure 5.7. Cost vs. diameter for the four tunnel excavation methods

Table 5.9. Summary of fitted curves for the four tunnel excavation methods.

Excavation method	Data Points	R^2	Equation fitted to the curve
TBM	21	0.10	$Cost = 4.9989D^{1.2844}$
Blast and drill	15	0.84	$Cost = 2.487D^3 - 54.033D^2 + 376.82D - 793$
Cut and cover	13	0.29	$Cost = -5.7445D^2 + 115.05D - 278.43$
Mixed methods	28	0.15	$Cost = 0.6533D^2 + 7.4594D + 85.75$

Multicollinearity test was performed on the two sets of data. Sonmez (2008) refers to collinearity/multicollinearity as the existence of high correlation when one independent variable is regressed among the other variables. According to Belsley et al. (1980), significant collinearity could contribute to poor hypothesis testing, estimation, and forecasting. The variance inflation factor (VIF) was used to assess the impact of multicollinearity among the independent variables in the function. In cases where multicollinearity is present, the independent variables are highly correlated with each other which could cause logical and statistical challenges. The inbuilt function in Minitab was used to evaluate multicollinearity characteristics of the data. A VIF value of less 10 indicates that there is no collinearity (Chatterjee and Price, 1991; Stevens, 1996). A collinearity test was performed for the final regression functions developed for both sets of data. The VIF results for the two functions indicated that multicollinearity was not a problem. The length of tunnel and diameter of tunnel variable used to develop the hard rock function had the highest VIF value of 1.02 for both variables. In the soft rock function, the highest VIF value was 9.18. From the results, collinearity did not affect the function, as the VIF values calculated were less than those proposed in Chatterjee and Price (1991).

The robustness and appropriateness of the tunnel cost estimation functions were determined by analyzing different statistical parameters as such: the R-squared value, the adjusted R-squared value, the p-values of the null hypothesis, and the standard error of the coefficients. The statistical parameters aided in making decisions of the independent variables elimination and/or inclusion in the TCEF. Statistical parameters measured the extent of variability in the TCEF to indicate the contribution of each parameter to the function to identify redundant independent variables, and also which independent variables would be eliminated from the function to improve its performance. The p-values were obtained from the statistical output of each model. The p-value provided the basis to determine whether there was enough evidence for inclusion and/or elimination. The summarized statistics for the two developed functions (Equation 7 and 8) are given in Table 5.10.

Table 5.10. Summary of statistics for the functions developed.

Parameter	Hard rock function	Soft rock function
Standard error	0.919527	1.108
R^2	35	97
Adjusted R^2	31	96
p-value	0.001	0.000

Standard errors of estimate for the hard rock function show that the error is 0.92% which is better compared to 5% confidence interval for the hard rock function. On the basis of the R-squared values of regression analysis, hard rock function has 0.35. The R^2 values for the hard rock function show that it is not a good fit for the data. For the hard rock function, the p-value was 0.001. For soft rock function, the standard error of estimate was 1.1% as compared to 5% confidence interval, which is better. The R^2 and adjusted R^2 for the soft rock were 97% and 96%, respectively. The function did not account for 3% of the data. The p-value for the soft rock function was 0.000. It should be noted that a good fit does not necessary mean that the predictions are accurate.

5.10.4. Prediction of tunnel costs

After the best fit TCEF algorithms were established, the functions were used to predict tunnel project costs and the results were compared to the original tunnel cost. Two methods were employed to quantify the goodness of fit between the modeled tunnel costs and the original costs. The two methods used were the normalized objective function (NOF) by Ibbitt and O'Donnell (1971) and the modeling efficiency (EF) by Nash and Sutcliffe (1970). The values of both NOF an EF and given by Equations 5.9 and 5.10, respectively.

$$NOF = \frac{1}{TCE_{Orig}} \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(TCE_{orig,\,i} - TCE_{\text{mod},\,i}\right)^2} \tag{5.9}$$

$$EF = 1 - \frac{\sum_{i=1}^{n} \left(TCE_{orig,\,i} - TCE_{\text{mod},\,i}\right)^2}{\sum_{i=1}^{n} \left(TCE_{orig,\,i} - \overline{TCE}_{orig,\,i}\right)^2} \tag{5.10}$$

Where, *TCEF orig,i*, is the original tunnel cost, *SF mod,i*, is the tunnel cost based on the fitting model, $\overline{TCE}_{orig\,i}$ is the mean original tunnel cost, *n* is the number of observations. The best values for NOF and EF should be close to 0 and 1 respectively.

From the two equations developed, the length and diameter of the tunnel affect the tunnel cost in a linear manner for the hard rock dataset. For the second equation, the length of tunnel and diameter of tunnel affect tunnel cost in a non-linear manner for the soft rock data set. As a check, the algorithms developed from the regression analysis were used to calculate tunnel costs for both hard rock and soft rock data sets, and then compared with the input data set.

5.10.5. Predicted versus actual tunnel costs for hard rock dataset

In the case of the hard rock data set, the best fit model was Equation 5.7. The model expressed tunnel cost as a function of tunnel length, and diameter of tunnel. The function was used to predict the hard rock tunnel cost and compared with the data set (Figure 5.9). Figure 5.8 shows the graph of actual tunnel costs versus predicted tunnel cost (Eqn. 5.7) and predicted tunnel cost (Eqn. 5.8). From Figure 5.8, it can be noted that Equation 5.7 cost prediction is very close to the actual tunnel costs. Apart from some three tunnel projects, the function seems to predict tunnel costs well with cost underestimation or overestimation ranging from -60% to +110%. This accuracy corresponds with Class 5 of AACE international of -50% to +100% (AACE 1998).

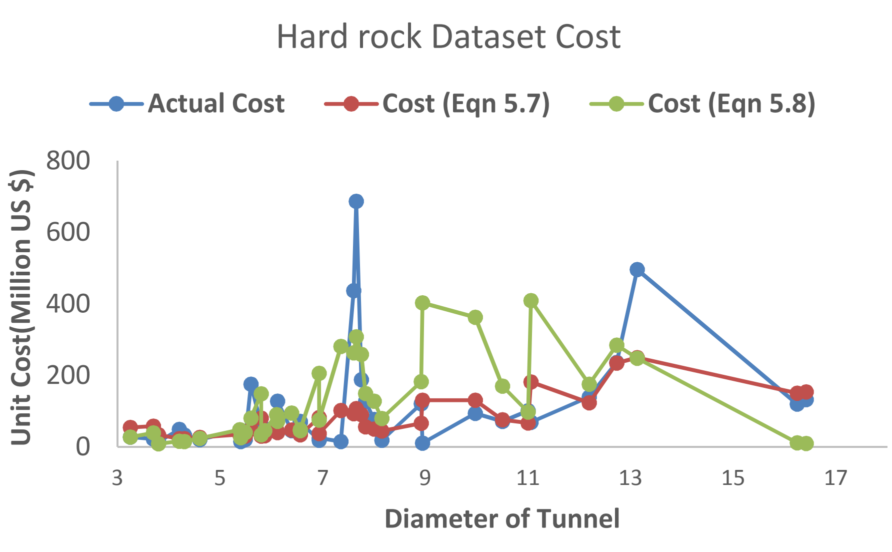

Figure 5.8. Actual tunnel cost versus estimated costs of various functions

5.10.6. Predicted versus actual tunnel costs for soft rock dataset

For the soft rock data set, the best fit function was Equation 5.8. The model expressed tunnel cost as a function of length of tunnel, diameter of tunnel, and diameter of tunnel squared. The actual tunnel cost versus the estimated tunnel cost using Equation 5.7 and Equation 5.8 are shown in Figure 5.9. From Figure 5.9, Equation 5. 8 provide a better prediction of the actual tunnel cost. The accuracy of cost prediction is the same range as for Equation 5.7.

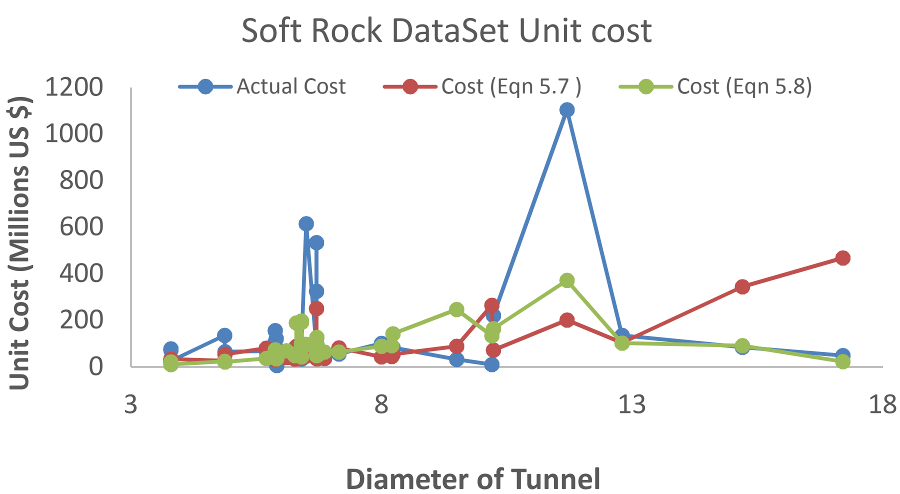

Figure 5.9. Actual tunnel cost versus estimated costs of various functions

The results of the predicted and actual costs for the hard and soft rock datasets are shown in Figures 5.8, and 5.9, respectively. It was observed that both Equations 5.7 and 5.8 for hard and soft rock, respectively give better results when used for each particular data set. The results suggest that each equation can only accurately predict the costs for its own class and are not interchangeable. The two equations developed could predict tunnel costs within an accuracy range of -60% to +110%, which compares well with Class 5 of the AACE international classification system. Both hard and soft rock functions were developed on the basis of linear and nonlinear relationships between the independent variables and the cost of transportation tunnel projects.

5.11. Summary

Calculating initial cost estimates using traditional cost estimation techniques and the associated project complexity, undefined scope, new technologies, and the uncertain nature of geological conditions have contributed to cost and schedule overruns for transportation tunnel projects at the feasibility phase. Construction of tunnel projects involves significant risk and uncertainty (Cheng et al., 2013; Hwang, 2011). Past reports have often shown the extent of cost underestimation, schedule growth, and high project contingency in transportation tunnel projects (Flyvbjerg et al., 2002, 2003b, 2004; Shane et al., 2009). The impact of inaccurate estimates has undermined public confidence in transportation tunnel projects financed by public organizations (Flyvbjerg et al. 2009, and Schexnayder et al. 2003). Currently, there is lack of a viable solution to the problems mentioned. Therefore, this research explored the body of knowledge on parametric cost estimating for transportation tunnel projects. It focused on identifying tunnel variables that significantly impact tunnel construction cost, and the development of a cost estimation function for use in the initial estimation of transportation tunnel project costs. Linear regression analysis was employed to develop parametric cost estimation functions for hard and soft rocks in transportation tunnel projects. The data of 79 transportation tunnel projects in North America, consisting of two samples of 38 hard rock tunnel projects and 41 soft rock tunnel projects, were used to develop the functions.

Tunnel variables significantly impacting tunnel costs were identified through the present research. The tunnel variables identified were then used to develop parametric functions on the basis of soft and hard rock for transportation tunnel projects using data from North America.

Regression analysis methodology was used to develop the functions. The robustness and appropriateness of the regression methodology was analyzed by: the R-squared value, the adjusted R-squared value, the p-values of the null hypothesis, the standard error of the coefficients, the sum of squares of regression, and the variance of inflation factor of the algorithms. The parametric cost estimating functions developed could be used to estimate initial costs at the screening/feasibility phase for tunnel projects. The proposed functions provide realistic results (-60% to +110%) compared to Class 5 of AACE International of -50% to +100% at the screening/feasibility phase of a transportation tunnel project. However, there is need to develop an electronic database for transportation tunnel projects to enhance the predictability of the functions, as well as identifying all the variables impacting tunnel cost.

CHAPTER 6. UNCERTAINTY MODELING AND RISK ANALYSIS OF TRANSPORTATION TUNNEL PROJECTS

6.1. Abstract

This chapter of the dissertation addresses uncertainty modeling and risk analysis of transportation tunnel projects at the feasibility phase. Past studies show that cost underestimation is often widespread in the construction of infrastructure projects. Cost underestimation is, in fact, a common occurrence in tunnel construction projects compared to surface infrastructure projects. Tunnel construction work is wrought with uncertainties and risks where ground conditions are difficult to predict prior to construction compared to conventional surface structures. Cost estimates are a major component of a tunnel project and their inaccuracies, associated risks vary with the different project stages and increases with the project's complexity. In the feasibility stage, cost estimates of a tunnel project depends on numerous risk factors as described in Chapter 2. The top ten risk factors identified in Chapter 2 contributing to cost underestimation in transportation projects were engineering and construction complexities, geological/ground conditions, poor estimating, economic and market conditions, environmental requirements, scope changes, size of project, technological innovation, political requirements, and contract document conflicts. Risk factors were identified through a systematic literature review. Parametric cost functions were developed by considering the risk factors identified. The developed functions were used to analyze two transportation tunnel projects to demonstrate their effectiveness and a cost uncertainty function framework is developed.

6.2. Uncertainty and Risk Analysis Methodology

Realistic cost estimates are required by agency/owner and contractors to make decisions regarding the construction of a transportation tunnel project. GAO reports show that projects overrun their budgets because the original cost estimates are unrealistic (2009). It is, in fact, important that if a realistic cost estimate is to be prepared extra dollars should be included to address the uncertainty of the cost estimate. Risks are also inherent with cost estimating techniques used to produce estimates. It is necessary to account for such risks by performing uncertainty and risk analysis of tunnel project costs to capture the uncertainty associated with the estimates and cure the effect cost underestimation following the steps shown in Figure 6.1.

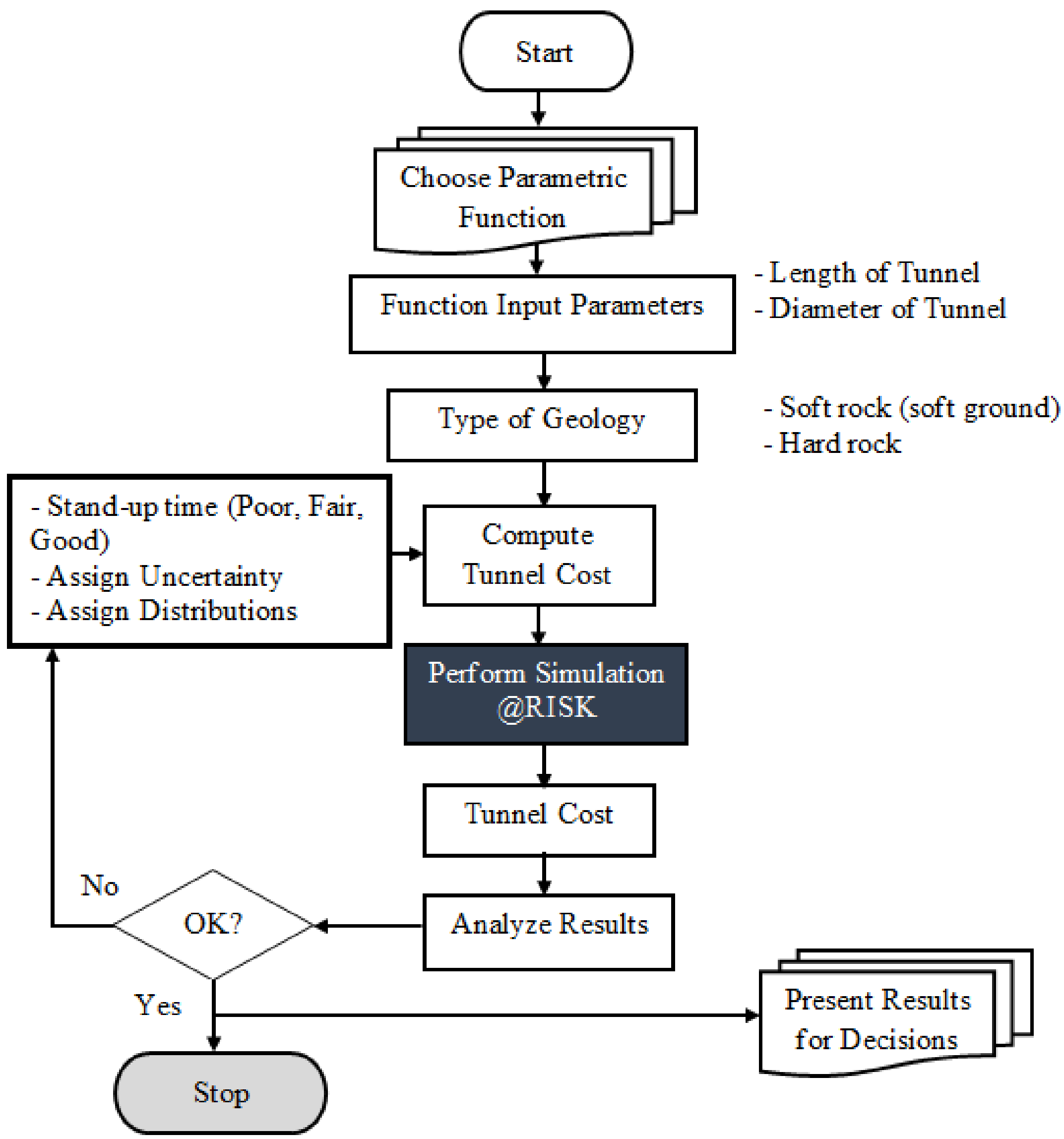

Figure 6.1. Uncertainty and risk model flow

The section commences with the introduction of risk and uncertainty analysis in the construction of transportation tunnel projects describing and defining the two terms, causes of risk and the strategies employed to overcome risk. Next, risk and uncertainty analysis steps of cost uncertainty function formulated for the generalized computation framework are description and explanation of cost uncertainty and risk in transportation tunnel projects; develop tunnel parametric cost functions; specify probability distributions to model uncertainty; assign uncertainty correlations to cost variables; perform simulation; analyze the results; determine, allocate, and phase risk costs; and results for decisions

6.2.1. Cost Uncertainty and Risk in Transportation Tunnel Projects

Cost estimation of transportation tunnel projects is a complex process with widespread cost, schedule, and contingency underestimation as well as uncertainties and risks which increase with the project's complexity. Some of the current cost estimation tools used to calculate the cost estimate for transportation tunnel projects however do not consider the concept of uncertainty and risk. For such techniques to address uncertainty and risk successfully, it is important to define the two terms. Risk is defined differently by professionals within the construction sector. Kaplan (1981) defines risk as the possibility of a loss or injury together with the degree of probability for such a loss. A number of reports addressing uncertainty and risk in transportation infrastructure projects have been prepared by organizations and professionals. Common definitions of risk reported in the project management and construction engineering management literature are presented:

- PMI (2008): risk is "an uncertain event or condition that, if it occurs, has a positive or negative effect on a project's objectives."

- WSDOT (2005): risk is "an uncertain event or condition that, if it occurs, has a positive or negative impact on a project."
- WSDOT (2008): risk is "a combination of the probability of an uncertain event and its consequences."
- Anderson et al. (2007): risk is "the combination of the probability of an adverse event and its consequences."
- Cabano, (2004): risk is "anything that influence the planning and execution of the project"
- HM Treasury (2004): risk is an "uncertainty of outcome, whether positive opportunity or negative threat of actions and events."
- Molenaar et al. (2010): risk is "an uncertain event or condition that, if it occurs, has a negative or positive effect on a project's objectives."
- Caltrans (2007): project risk is "an uncertain event or condition that, if it occurs, has a positive or negative impact on at least one project objective."
- Einstein (2002): "Risk can be described as $R = P[U]x$ consequence, where R is risk and $P[U]$ is the probability of unsatisfactory performance, and where the consequence can be expressed in financial or other terms."

Risk is associated with either an event or with some consequences of the project's objectives (Caltrans, 2007; Molenaar et al., 2010; PMI, 2008; WSDOT, 2005) or a combination of the probability and the consequences of an event (Anderson et al., 2007; WSDOT, 2008; Einstein, 2002). It is also observed that even with the same organization, there is no uniformity in the definition of risk (WSDOT, 2008). In the tunneling work the uncertainty is associated with scope risks, cost risks, and schedule risks. Therefore, risk is an important component of cost that must be addressed and not avoided. Risk can be divided into five component parts: uncertainty, hazard, damages, safeguard, and probability (Kaplan, 1981).

Uncertainty points to lack of knowledge due to the randomness when something is not known; thus difficult to determine the final result of the event (Kaplan, 1981). This is typical when performing cost estimation for transportation tunnel projects where several variables are unknown since the construction of tunnel projects are populated with uncertainties. Uncertainty can have a positive or negative impact on the project objectives. It is an opportunity if it has a positive impact and a threat if it has a negative impact on the project objectives. Uncertainty originates from the variability in the construction process, the correlations between construction costs, and the occurrence of disruptive events.

Hazard, a component of risk, is the source of danger that can cause damages if negatively applied (Kaplan, 1981). While on the other hand, damages are the quantifiable negative outcomes of an event (Kaplan, 1981). For example project construction delays where the contractor has to pay damages due to schedule delay and liquated damages. In cases where risk is unquantifiable, safeguards should put in place. Safeguards are measures taken to control an event's negative outcome, also termed contingency (Kaplan, 1981). Contingency is a sum value set aside as a lump allowance to act as a buffer to recover from risk. Probability, another term associated with risk, is used to compute the outcome of a given event by performing repeated trials associated with the event (Kaplan, 1981).

According to Kaplan and Garrick (1981), risk analysis and risk quantification are performed to provide input to an underlying decision which requires not just risks but also other forms of costs and benefits. Ashley et al. (2006) discusses the importance of incorporating risk assessment, risk allocation, and risk management in infrastructure projects. Risk management is the process for identifying, analyzing, and planning risk interventions throughout all stages of the tunnel construction project. Risk identification is not an easy task, because the tunnel construction projects involve a high level of uncertainty and complexity. Mitigation strategies such as risk-elimination, risk-reduction, and risk-allocation methodologies are applied by choosing suitable design solutions to shift the odds of a project's success or failure (Gabel, 2010).

6.2.2. Causes of Risk

The uncertainty and risk factors contributing to cost underestimation in transportation tunnel projects are described in Chapter 2 of the dissertation. The risk factors identified are grouped into four groups: internal factors, external factors, project specific factors, and other factors (Membah and Asa, 2015). In the categorization, some risk factors overlap in the internal and external groups. Other literature sources report risk factors as being grouped into technical, economic, political, and psychological (Flyvbjerg et al., 2003). All the stages of a tunnel project are influenced by several uncertainties. These can be either usual uncertainties which can be encountered during the course of tunnel implementation, or may be due to the occurrence of extraordinary tunnel construction failures. Tunnel failures are risk factors that may occur during the construction stage of a tunnel project. Tunnel construction failures are catastrophic events, which adversely affect the construction process of an underground structure. It is important that tunnel failure risks be considered when preparing cost estimates. The most common reported tunnel failures are inflow of sand and gravel, tunnel penetrating soft ground, portal collapse and cave-ins, fractured rock, design and management errors, insufficient overburden, uncontrollable muck-flow, lateral support collapse, and diaphragm wall collapse. The tunnel construction failures can also cause damage to adjacent structures and thus causing significant unplanned expenditure on the project development.

6.2.3. Strategies to Overcome Risk

As is often the case with complex underground projects, tunnel projects are prone to cost underestimation, construction delays, and sometimes expensive litigation due to unpredictable aspects of the geotechnical conditions in which the tunnel is being constructed. The geotechnical characteristics are sometimes difficult to be fully understood until well after a substantial commitment has be made to its implementation. There is a possibility of cost underestimation which may be caused by any number of risk factors, such as lack of adequate planning and investigation, encountering unanticipated conditions along the tunnel alignment leading to slower production, impact technology and techniques used to excavate the tunnel, and different tunnel support requirements.

Anderson et al. (2007) proposed eight strategies to counteract the risk factors contributing to cost underestimation in infrastructure projects. The eight strategies that can affect the accuracy and consistence of project estimates and cost are:

- Management strategy: manage the estimation process and costs through all the stages of project development. This strategy should foster accuracy, consistency, and transparency, and it involves training of the organization personnel, establish estimation processes, and allow critical reviews of all estimates.
- Scope and schedule strategy: formulate processes to control project scope and scope changes.
- Off-prism strategy: utilize proactive methods to engage external stakeholders and assess the macro-environmental conditions that can influence the project costs. External

stakeholders, macro-environmental conditions, market and macro-economic changes are called off-prism cost drivers as they are not within the tunnel prism. The off-prism strategy allows for the sensitization and reaching out the community to air their interest or concerns and evaluate market and macro-economic conditions.

- Risk strategy: risk identification, quantification of their impact on cost, and mitigation measures to address the risks.
- Delivery and procurement strategy: apply appropriate delivery methods to better manage cost since project delivery influences both project risk and cost.
- Document quality strategy: use improved project documents to promote accuracy and consistency of cost estimates.
- Estimate quality strategy: utilize qualified personnel and uniform approaches to achieve improved estimate accuracy and consistency.
- Integrity strategy: put in place checks and balances to maintain estimate accuracy and to minimize the influence of outside pressures that can cause biases in the estimates.

Risk factors that contribute to project cost underestimation are documented in several studies (Flyvbjerg et al., 2002; 2003; 2004; Molenaar, 2005, Anderson et al., 2007; Shane et al., 2009). This section of the chapter focuses on the risk strategy to counteract cost underestimation in transportation tunnel projects. The risk strategy consists of six steps proposed by Ashley et al. (2006). The six primary steps are: 1) risk identification, 2) risk assessment 3) risk analysis 4) risk mitigation and planning 5) risk allocation, and 6) risk monitoring and updating.

Risk identification is the first step of the risk management strategy (Ashley et al., 2006; Anderson et al., 2007). It consists of identifying, categorizing, and documenting risks that could affect the project. Risk identification involves investigation of project description, design, cost estimates, construction schedules, work breakdown structure, and others. The list of risks that is prepared in this step is used in the subsequent steps of the risk management strategy (assessment, analysis, mitigation, allocation, and monitoring). The transportation agencies and project management entities have developed tools which can be used to identify potential risk in projects (Molenaar et al., 2010). The tools to use during risk identification include: red flag items, risk checklists, assumption analysis, expert opinions, SWOT (strengths, weaknesses, opportunities, threats) analysis, risk management plan, risk workshops, risk register, and risk breakdown structure. A number of these tools can also be used in the risk analysis step (expert interviews, risk management plan, risk workshops and risk register).

Risk assessment is the process of quantifying the risk events documented in the preceding identification step. This is the process of making a decision on whether existing risks are tolerable and present risk control measures adequate, and if not, whether alternative risk control measures are justified or will be implemented (Melenaar et al., 2010). Risk assessment and risk analysis steps might be combined in some cases when developing a risk strategy.

Risk analysis is the process of evaluating risks documented in the risk identification step to assess the range of possible project outcomes (Molenaar et al., 2010). It determines the probability of occurrence of the risk and its consequences of the risk does occur. Risk quantification uses qualitative and quantitative techniques to analyze the risks. The qualitative techniques used to analyze risks are checklists, brainstorming and Delphi, assumption analysis or data precision ranking, probability and impact description, probability-impact rating tables, cause-and-effect diagrams, expert judgment, and event and fault trees.

Several quantitative tools are used to analyze the risk of a tunnel transportation project. The most commonly used quantitative risk analysis tools are: sensitivity analysis, expected value tables, percentage contingency, triple estimate and probabilistic sums, Monte Carlo simulations, decision trees, probabilistic influence diagrams, multi criteria-making support methods, process simulation, and system dynamics (Molenaar et al., 2010).

Risk mitigation and planning is the process of exploring risk response strategies for the key risks identified in the qualitative and quantitative risk analysis. It identifies the best response strategy suitable for each risk and designs specific actions to implement the selected risk response strategy. Caltrans (2007) proposes four risk response strategies: avoidance where the project plan is changed to eliminate a risk, transference-the financial impact of the risk is transferred by subcontracting part of the work, mitigation-the probability of occurrence or the consequences of a risk are reduced to an acceptable threshold, and acceptance where certain risk are accepted.

Risk allocation is the process of identifying and allocating risks to the party best able to manage them. The party in this case could be a construction manager, an agency planner, engineer, or contractor. Risk allocation should follow the outlined principles: allocate risk to the party best able to manage it, allocate a risk alignment with project objectives clearly defined, share a risk when appropriate to accomplish project goals, and allocate a risk to promote alignment with customer-oriented goals (Ashley et al., 2006, Molenaar et al., 2010).

Risk monitoring and updating is the process of systematically tracking predetermined risks, identifying new risks, effectively managing the contingency reserve, and capturing lessons learned for future risk assessment and allocation efforts. Risk monitoring and updating should performed throughout the life of the project. Risk monitoring and updating is composed of developing comprehensive reporting procedures, monitoring risk and contingency reserves, and providing feedback for future risk management (Ashley et al., 2006, Molenaar et al., 2010).

Although Monte Carlo simulation is suggested as the appropriate technique to use when determining contingency, it has challenges and drawbacks (Hollmann, 2007). Hollmann proposes the inclusivity of the following features when performing risk analysis: identify and understand the risk drivers, recognize the differences between systemic and project specific risk drivers, address systemic risk drivers using stochastic models, address project specific risk drivers using methods that explicitly link risk drivers and cost outcomes, and if the technique is using Monte Carlo, dependencies must be addressed.

6.3. Parametric Cost Estimation Functions

Parametric cost estimating functions (relationships) (CERs) developed in Chapter 4 are summarized in Tables 6.1 and 6.2. The CERs were developed using Excel and Minitab software. The results obtained when using the CERs indicated that all the best fitting models were either a function of one variable or more than one variable (diameter of tunnel, length of tunnel, and depth of tunnel overburden). The models considered here performed significantly better than the other models without the same combination of independent variables.

Table 6.1. Summary of cost functions for type of geology.

Mode of transportation	Type of geology	Function	Comment
Highway	Hard rock	Cost = $0.6981De^2 + 0.0481De + 185.17$	
Railway	Hard rock	Cost = $0.2605De^2 + 1.0041De + 145.6$	
	Soft rock	Cost = $-0.5657L^3 + 16.708L^2 - 52.973L + 175.55$	
Metro	Hard rock	Cost = $-1.613L^3 + 31.053L^2 - 117.33L + 194.53$	
	Soft rock	Cost = $1.5769L^3 - 52.029L^2 + 507L - 585.44$	General equation

Table 6.2. Summary of cost functions for tunnel excavation method.

Mode of transportation	Method of tunnel excavation	Function	Comment
Highway	Drill and blast	Cost = $21.362L^3 - 234.17L^2 + 746.82L - 507.42$	
	Cut and cover	Cost = $1.9888De^2 - 31.716De + 139.96$	
		Cost = e^(4.29+0.127Le+0.017Di+0.017Le*Di)	General function
Railway	TBM	Cost = $9.2677L^2 - 61.387L + 274.57$	
	Mixed methods	Cost = $9.2677L^2 - 61.387L + 274.57$	
		Cost = e^(3.669+0.0427De +0.1709Le)	General function
Metro	Mixed methods	Cost = $-3.6265De^3 + 169.2De^2 - 2402.4De + 10750$	
Subway	TBM	Cost = $-0.261De^3 + 15.108De^2 - 260.01De + 1453.5$	
		Cost = e^(0.0863De+0.2121Le+0.3494Di)	General function

6.4. Specification of Probability Distributions to Model Uncertainty

The normal and lognormal distributions were used to model CERs to perform uncertainty analysis. The assumption of normality permeates statistical modeling and analysis. The variables used in the calculation of the tunnel cost estimates were not normally distributed. This was true for all categories such as tunnel excavation methods, geology, and others. In order to account for the variability, and its accompanying uncertainty, probability distributions are employed in the tunnel cost estimates function. @RISK software was used to model tunnel cost estimation equations as probability distributions functions in order to capture the variability of the datasets. The tunnel cost function was simulated together with the statistical properties of the best fitted probability distributions and Monte Carlo simulations (MC) to calculate the cost estimates for the category in question. The following probability and MC simulations were used to simulate the tunnel cost estimates for the different categories:

Scenario 1: 1,000 at confidence interval (CI) of 80, 85, 90, and 95%

Scenario 2: 5,000 at CI of 80, 85, 90, and 95%

Scenario 3: 10,000 at CI of 80, 85, 90, and 95%

6.5. Simulations

Uncertainty analysis was performed using Monte Carlo simulation for the scenarios given. MC simulations help to produce more than one outcome for the tunnel estimate.

6.6. Analysis of Results

After running the simulation, the tunnel cost estimate results were plotted. The results of the simulation help to determine the level of probability in producing the tunnel cost estimate.

6.7. Distribution of Risk Costs

The risk and uncertainty analysis is aimed at ensuring the project cost, schedule, and contingency outcomes can be achieved. Cost uncertainty analysis quantifies the uncertainties associated with the variables of the cost function. The cost estimates can then be converted to into the year-dollars and the amount of contingency allocated to mitigate risks. Risks being mitigated should be known to aid in risk management.

6.8. Present Results for Decision Making

The results are presented to decision makers or agency to communicate the risks that contribute to the tunnel cost estimates. The results should provide for the then-year dollar risk allocated and the cost drivers that contribute to the cost estimate. The contributors to cost uncertainty should also be identified and any mitigation measures captured in the estimate.

6.9. Case Studies

This section briefly describes and examines the proposed cost function(s) of two tunneling projects. The function(s) developed is applied to the Port of Miami Tunnel and SR 99 Alaskan Tunnel. First, the functions are used to estimate costs for the Port of Miami tunnel to test its effectiveness in computing risk uncertainty. After the function(s) effectiveness has been determined, it is then used to estimate cost for the SR 99 Alaskan tunnel. In both cases, the TBM method was used to bore the highway tunnel projects. A number of functions were developed based on application, however, among these functions only two equations were appropriate to estimate tunnel cost. For the highway mode of transportation, two functions were developed; one based on the entire highway data and the second was based on soft rock data (Table 6.1). Among these functions none was developed based on TBM tunnel excavation method.

6.9.1. Port of Miami Tunnel

The Port of Miami Tunnel is a project executed to improve port access by connecting Watson Island and Dodge Island in Miami. The underground tunnel provides alternative direct link access to and from the Port of Miami with interstates 95 and 385. The Port Boulevard Bridge was the only link connecting the two man-made islands which made it difficult for motorists to navigate through city streets and the interstates highways, creating traffic backups.

In 1981, the Florida Department of Transportation (FDOT) commenced examining port access to link the Watson and Dodge Islands in Miami by considering different alternatives. A feasibility and cost study was conducted on the tunnel alternative in 1983, and the project was approved in 1984 for detail planning, design, and engineering (PD&E). In 1989, FDOT's department of construction began the tunnel PD&E study to develop and evaluate the cost for the alternatives to link the port and the interstate highway systems. The Port of Miami tunnel and access improvement project, in 2006, was advanced through a public-private partnership (PPP). The project consists of widening of the MacArthur Causeway Bridge widening, a tunnel connection from Port of Miami to Watson and Dodge Islands, and Port of Miami roadway system connections. After a long period of contract negotiations, a financial close for the project was achieved through a PPP contract to advance the bored tunnel originally estimated at $607 million in 2009. The contract was won by the Miami Access Tunnel Consortium. The Concessionaire's team comprised of Bouygues Civil Works Florida, which was the design-build contractor and Transfield Services Industry (TSI) as the Tunnel Operator. The key decision of using the concession approach was to access private sector expertise in construction, managing, mitigating and valuing risk, and providing additional sources of funding as well as accessing advanced technology. Figure 6.2 shows the Port of Miami Project location.

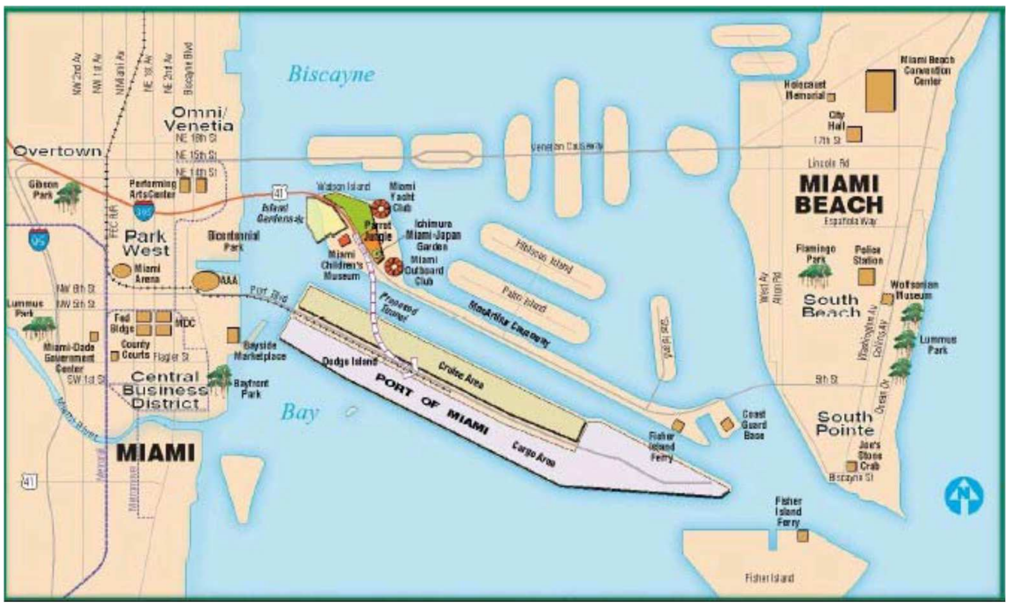

Figure 6.2. Port of Miami Project location (FDOT, 2006)

The two equations were setup in Excel and then simulated using @Risk software. The following equations were simulated: Cost (millions) = e^ (4.29+0.127Le+0.017Di+0.017Le*Di) (equation 6.1) and Cost (millions) = e^ (0.087 Le + 1.1904 Di – 0.0591 Di ^2) (equation 6.2). Three analysis scenarios were performed at 1,000, 5,000, and 10,000 iterations with confidence intervals at 80%, 85%, 90%, and 95%, respectively. Scenario 1 MC simulations using equation 6.1at the specified confidence intervals are depicted in Figures 6.3 to 6.6.

6.9.1.1 Scenario 1 (1,000 iterations)

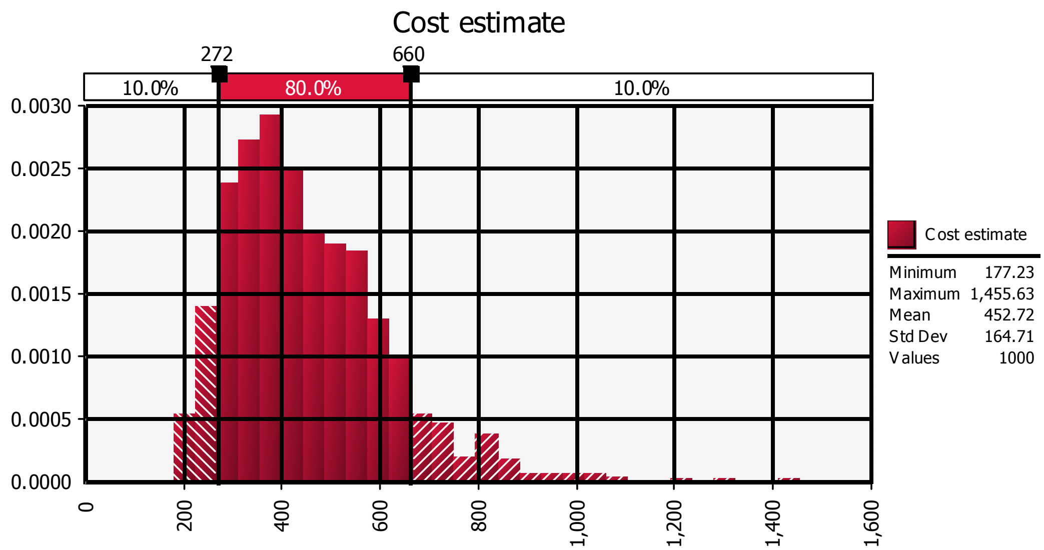

Figure 6.3. Miami tunnel project cost estimate (80% confidence interval)

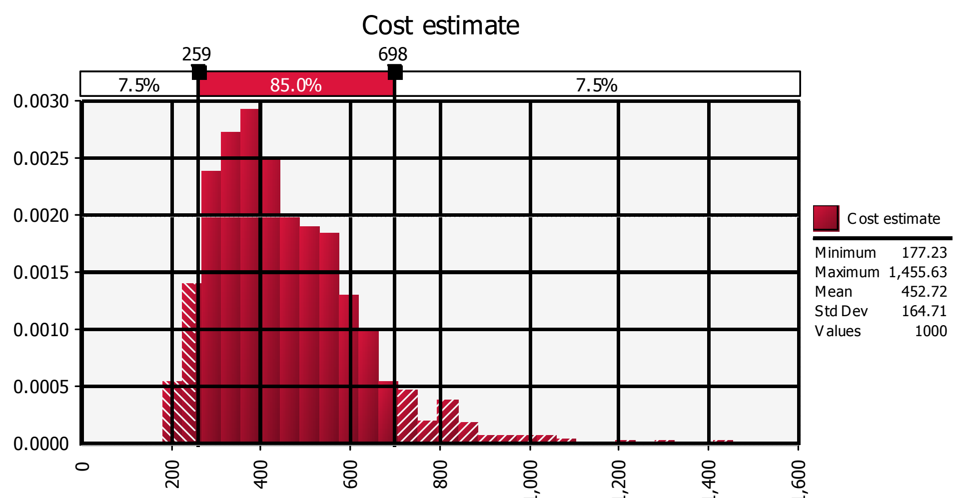

Figure 6.4. Miami tunnel project cost estimate (85% confidence interval)

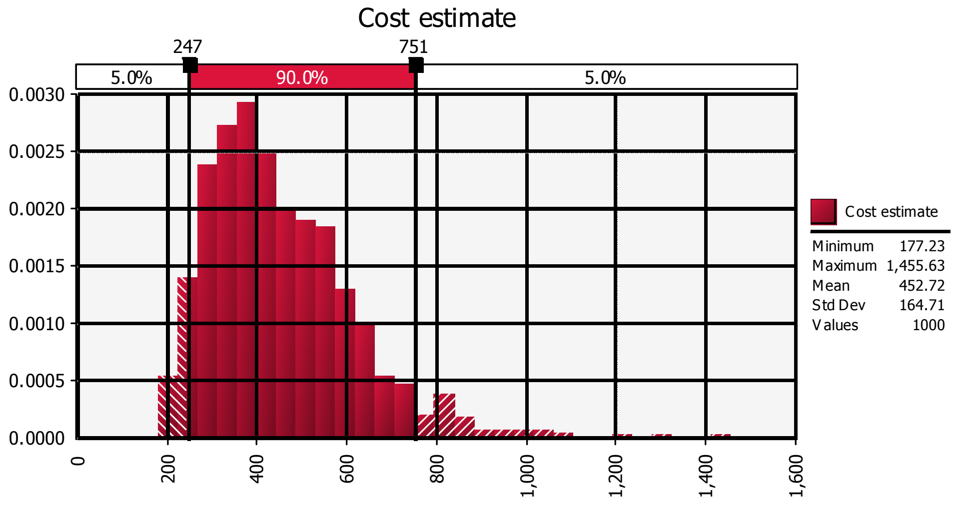

Figure 6.5. Miami tunnel project cost estimate (90% confidence interval)

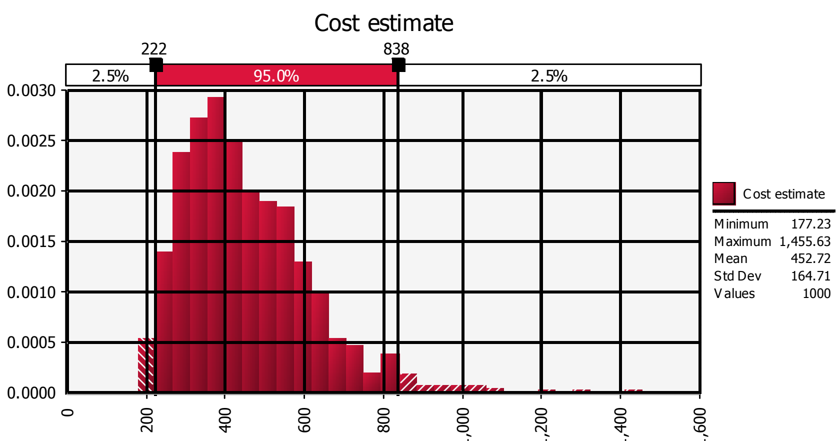

Figure 6.6. Miami tunnel project cost estimate (95% confidence interval)

The cost estimate ranges from a minimum of $272 million to a maximum of $660 million for the Miami tunnel project when factoring in uncertainty at 80% confidence interval. The cost estimate reaches a minimum of $222 million and a maximum of $838 million at 95% confidence interval with a standard deviation of $164.71 million. When using equation 6.2, the MC simulations are shown in Figure 6.7. Figure 6.7 shows the cost estimate from a minimum of $28 million to a maximum of $3,308 million. This equation is not considered for further analysis.

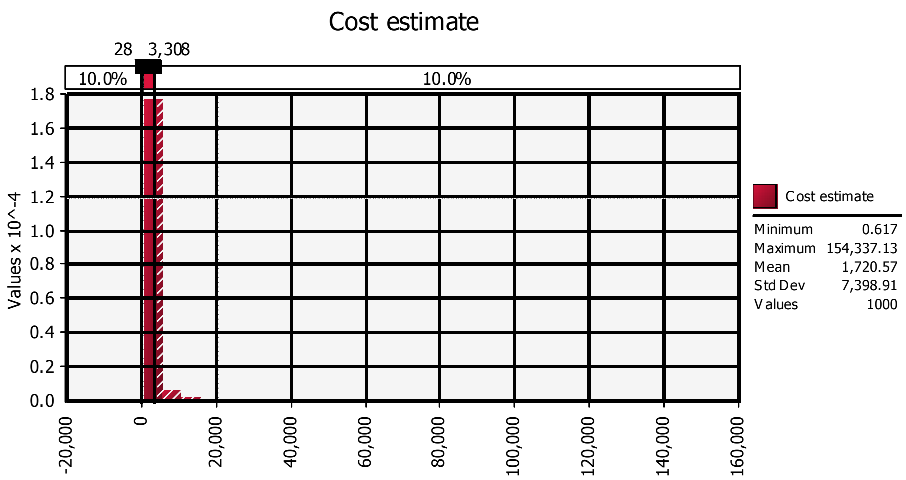

Figure 6.7. Miami tunnel project cost estimate (Second equation at 80% confidence interval)

6.9.1.2. Scenario 2 (5,000 iterations)

Scenario 2, MC simulations using equation 6.1 at the specified confidence intervals is depicted in Figures 6.8 to 6.11. The cost estimate ranges between a minimum of $274 million and a maximum of $671 million for the Miami tunnel project when factoring in uncertainty at 80% confidence interval. The cost estimate reaches a minimum of $224 million and a maximum of $843 million at 95% confidence interval with a standard deviation of $161.51 million.

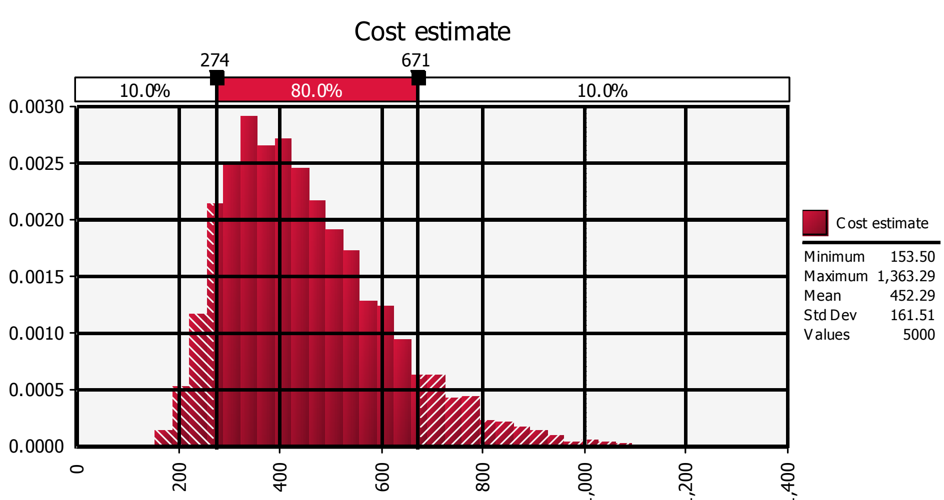

Figure 6.8. Miami tunnel project cost estimate (80% confidence interval)

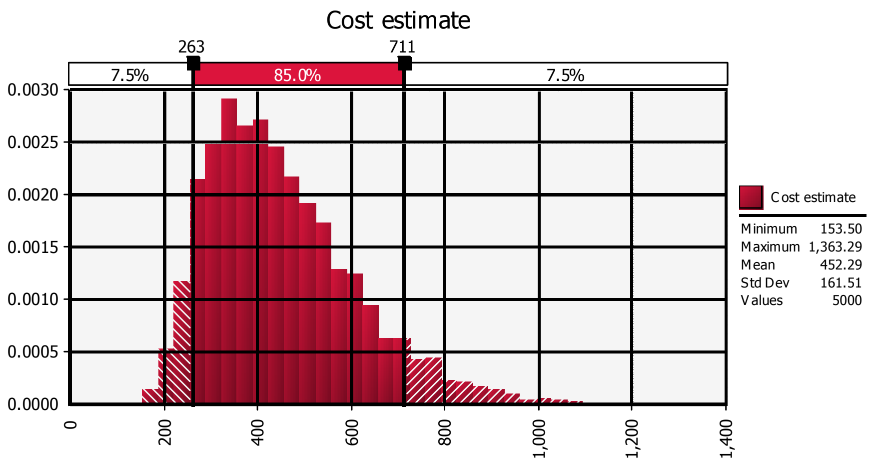

Figure 6.9. Miami tunnel project cost estimate (85% confidence interval)

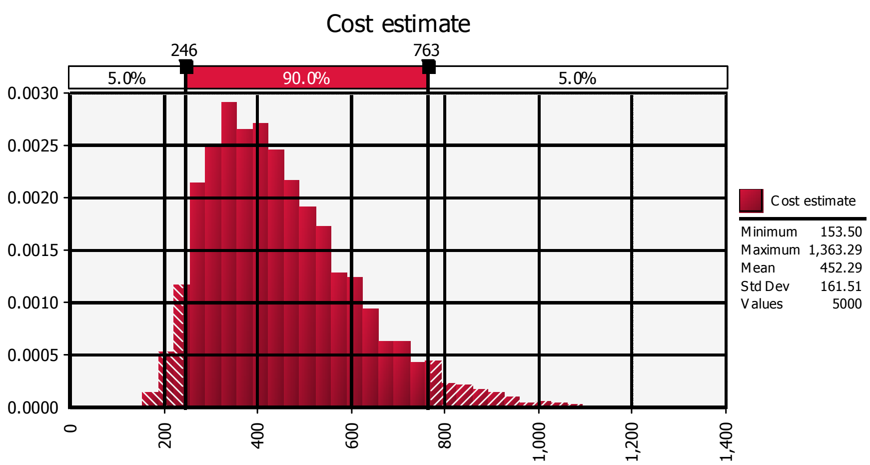

Figure 6.10. Miami tunnel project cost estimate (90% confidence interval)

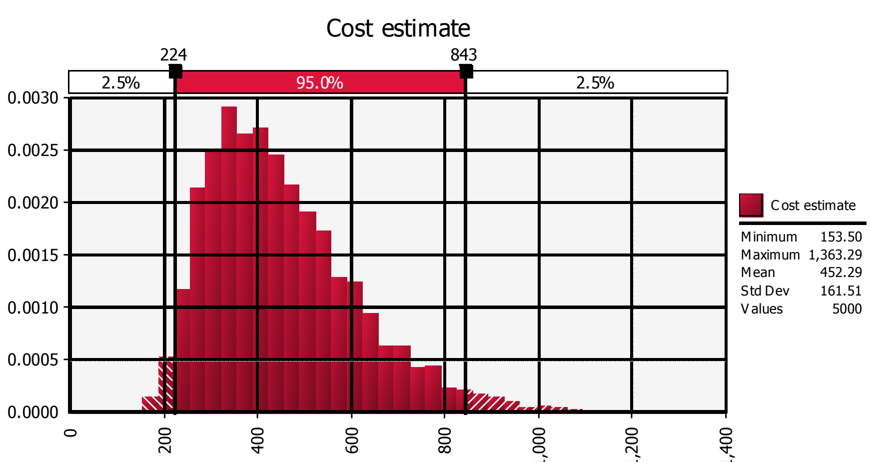

Figure 6.11. Miami tunnel project cost estimate (95% confidence interval)

Scenario 3, MC simulations using equation 6.1at the specified confidence intervals are depicted in Figures 6.12 to 6.15. The cost estimate ranges between a minimum of $271 million and a maximum of $673 million for the Miami tunnel project when factoring in uncertainty at 80% confidence interval. The cost estimate reaches a minimum of $222 million and a maximum of $833 million at 95% confidence interval with a standard deviation of $161.19 million. The cost estimation results for the three scenarios are summarized in Table 6.3. The three scenarios considered produced similar results, although the minimum is not comparable to the original estimate of $530.83 million.

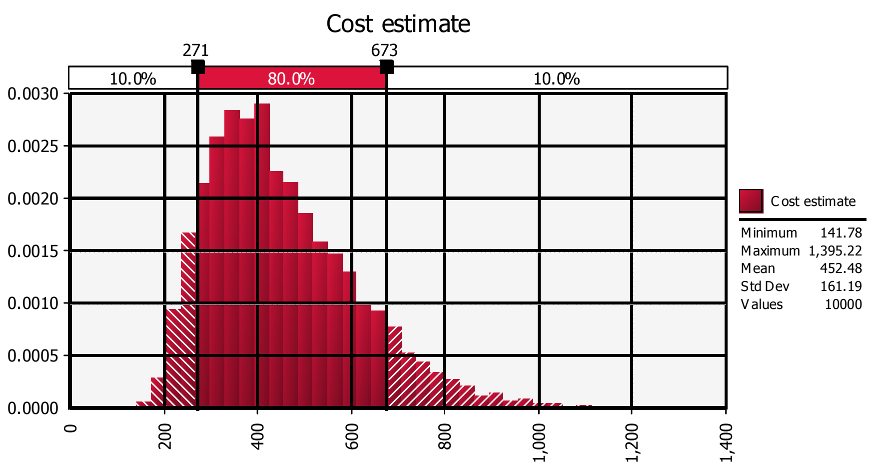

Figure 6.12. Miami tunnel project cost estimate (80% confidence interval)

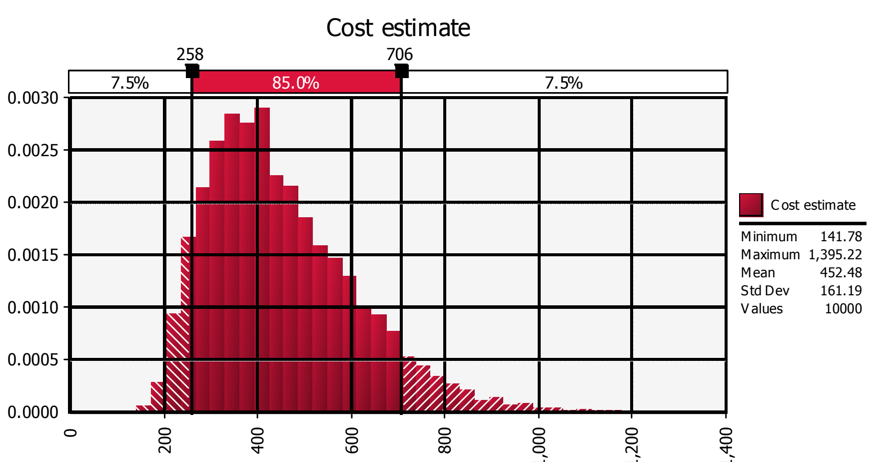

Figure 6.13. Miami tunnel project cost estimate (85% confidence interval)

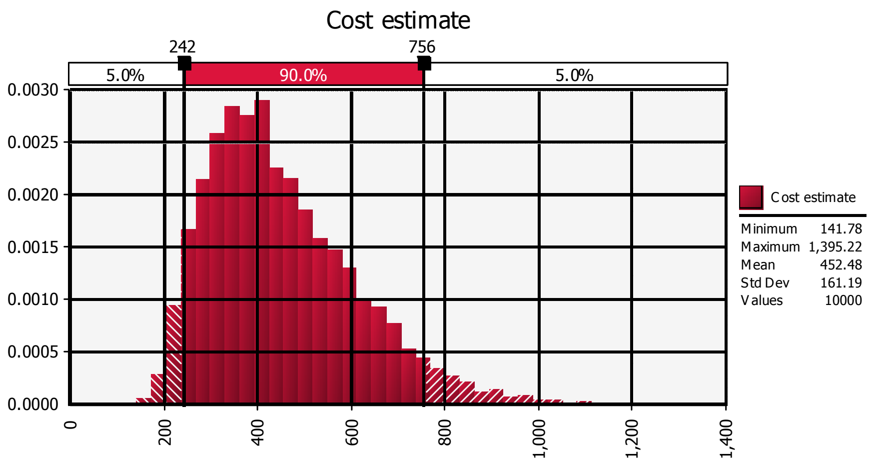

Figure 6.14. Miami tunnel project cost estimate (90% confidence interval)

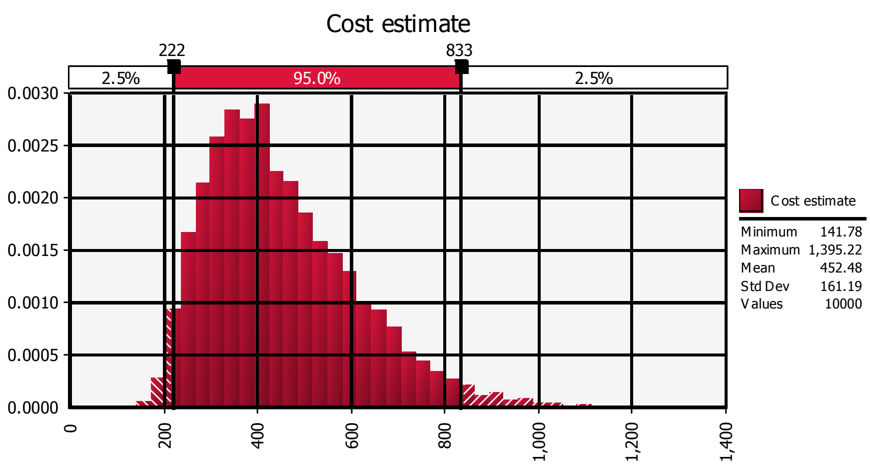

Figure 6.15. Miami tunnel project cost estimate (95% confidence interval)

Table 6.3. Summarizes the cost estimation results for the Miami Tunnel Project.

	80%		85%		90%		95%	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Scenario 1	272	660	259	698	247	751	222	838
Scenario 2	274	671	263	711	246	763	224	843
Scenario 3	271	673	258	706	242	756	222	833

All values are in US dollars

6.9.2. SR 99 Tunnel Project

The SR Tunnel project is a deep-bored tunnel underneath downtown Seattle to replace the central waterfront section of the SR 99 Alaskan Way Viaduct being built by the Washington Department of Transportation (WSDOT). When the tunnel is complete, it will connect to the new

SR 99 roadway south of downtown, and to Aurora Avenue in the north to maintain a vital link for people and goods. The 1950s double-deck viaduct has been showing signs of aging and deterioration, and the process of replacing SR 99 was accelerated by the Nisqually earthquake of February 2001, which caused significant damage to both the Viaduct and the Seawall along the adjacent waterfront. The viaduct stands on fill soil bounded by the seawall. Marine organisms have slowly eaten away parts of the seawall and weakened it. In case of an earthquake, since the fill soil is subject to liquefaction there might be catastrophic failure of the viaduct (WSDOT, 2011). After the 2001 earthquake, WSDOT hired consultants to conduct detailed evaluations of alternatives to repair or replace the viaduct and seawall. It took several years before a decision could be reached on the way forward on this project.

The tunnel project is part of the Alaskan Way Viaduct Program and consists of the South Portal Access, the bored tunnel, and the North Access Portal access, and other features (GBR, 2010). The project delivery method was a design-build contracting to advance the bored tunnel originally estimated at $1.35 billion (WSDOT, 2011). The contract was won by the Seattle Tunnel Partners composed of Dragados USA and Tutor Perini Corp. joint venture, with Frank Coluccio Construction, Mowat Construction, HNTB Corp and Intecsa-Inarsa. Although at the commencement of tunneling, cost related to tunnel work had reached $1.96 billion for the 2.75 kilometers (1.7 mile) and a diameter of 17.3 meters (57.5 feet) (see Figure 6.16).

The bored tunnel is located in Seattle, Washington state within the central portion of the Puget Lowland, an elongated topographic and structural depression bordered by the Cascade Mountains on the east and the Olympic Mountains on the west. The geological conditions consist of glacial and interglacial soil units typically of limited lateral extent and grade laterally, are inter-layered with, or may contain blocks of material from other stratigraphic units. The subsurface layers consist of the Holocene, Vashon and Pre-Vashon units.

Figure 6.16. SR 99 bored tunnel cross section – design concept corridor route (WSDOT, 2010)

For the risk-based uncertainty for estimate cost analysis, normal distribution values for input factors and beta distribution for the cost estimate were applied in the scenario simulation runs as aforementioned in section 6.4 using the @RISK (Palisade Corp., Ithaca, N.Y., 2015). For the MC simulations to reach a faster convergence, the Latin Hypercube stratified sampling technique was adopted. The same scenarios for Miami Tunnel Project were followed for performing risk uncertainty for the SR 99 bored tunnel project. For Scenario 1, MC simulations using equation 6.1 at the specified confidence intervals are depicted in Figures 6.17 to 6.20. The cost estimate ranges between a minimum of $502 million and a maximum of $1,990 million for the SR 99 tunnel project when factoring in uncertainty at 80% confidence interval. The cost estimate reaches a minimum of $342 million and a maximum of $3,154 million at 95% confidence interval with a standard deviation of $753.39 million.

6.9.2.1 Scenario 1 (1000 iterations)

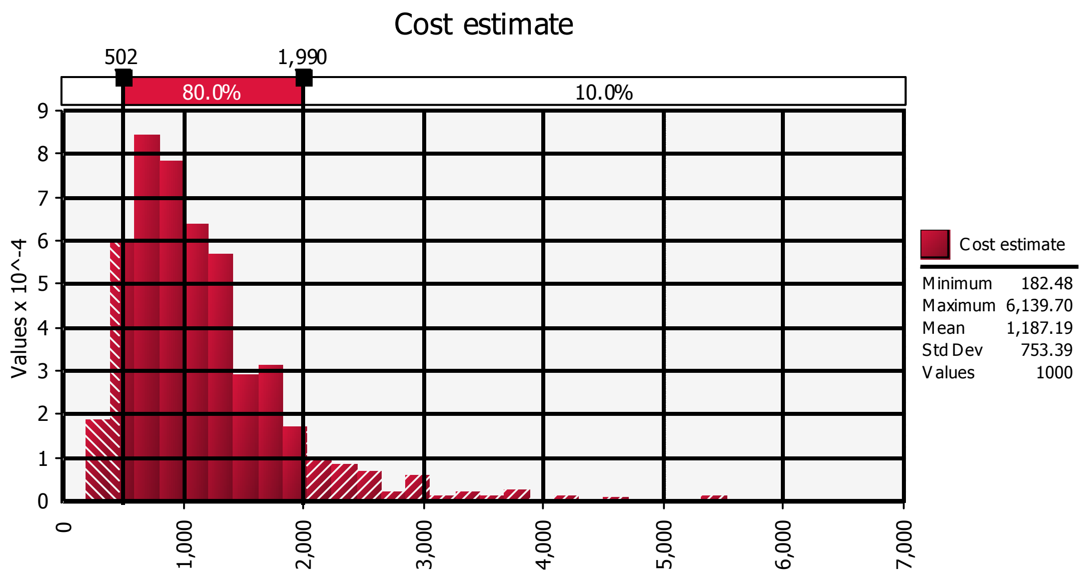

Figure 6.17. SR 99 tunnel project cost estimate (80% confidence interval)

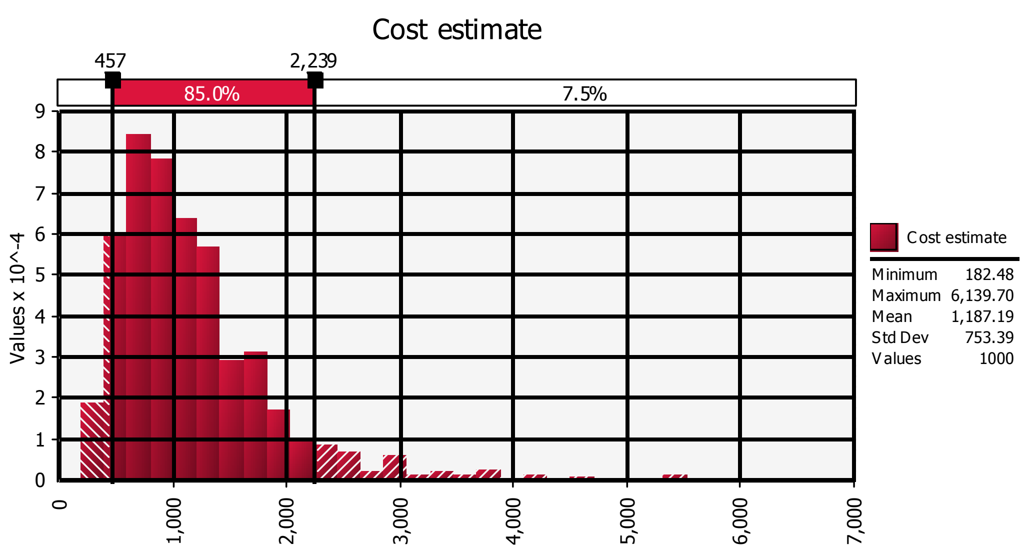

Figure 6.18. SR 99 tunnel project cost estimate (85% confidence interval)

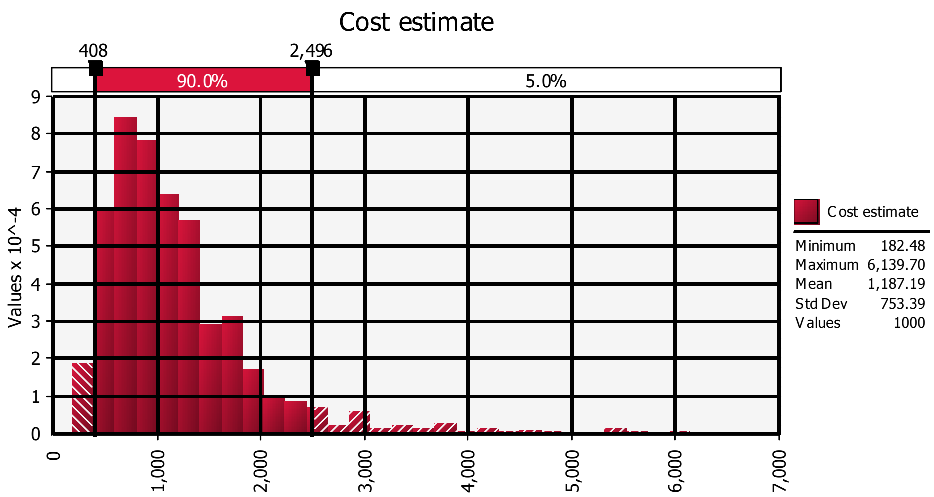

Figure 6.19. SR 99 tunnel project cost estimate (90% confidence interval)

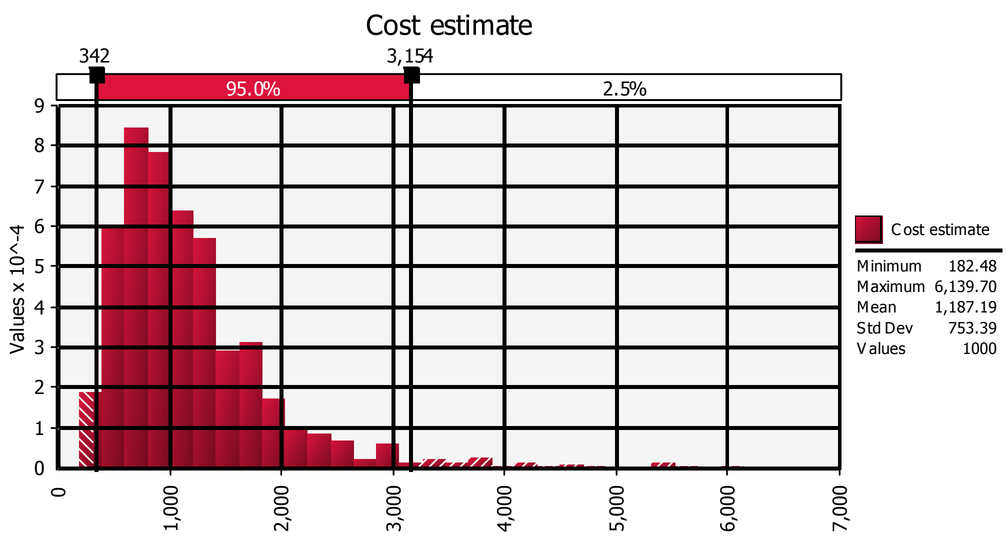

Figure 6.20. SR 99 tunnel project cost estimate (95% confidence interval)

6.9.2.2. Scenario 2 (5000 iterations)

Scenarios 2, MC simulations using equation 6.1 at the specified confidence intervals are depicted in Figures 6.21 to 6.24. The cost estimate ranges between a minimum of $494 million and a maximum of $2,099 million for the SR 99 tunnel project when factoring in uncertainty at 80% confidence interval. The cost estimate reaches a minimum of $346 million and a maximum of $3,123 million at 95% confidence interval with a standard deviation of $747.69 million.

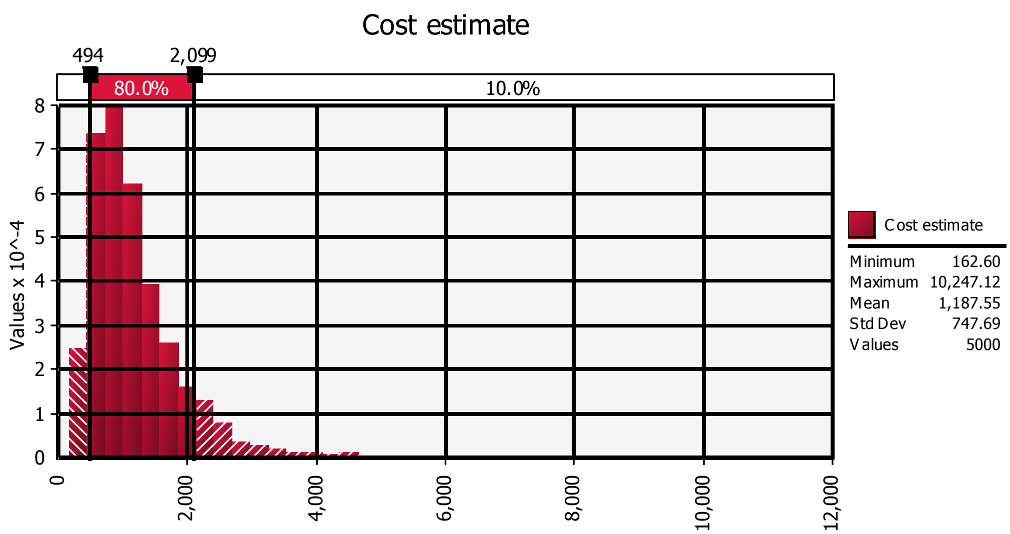

Figure 6.21. SR 99 tunnel project cost estimate (80% confidence interval)

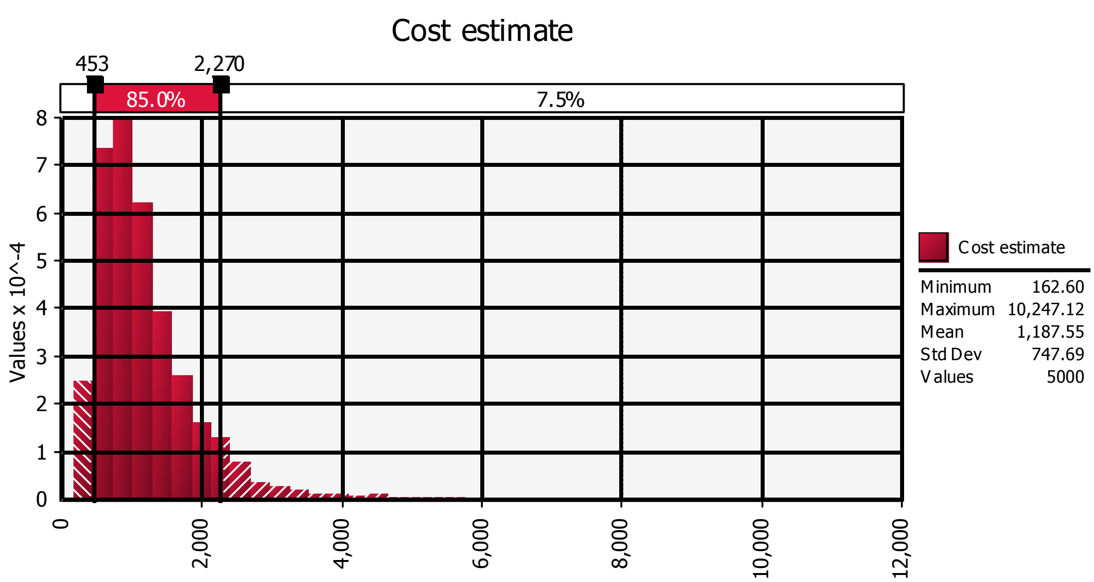

Figure 6.22. SR 99 tunnel project cost estimate (85% confidence interval)

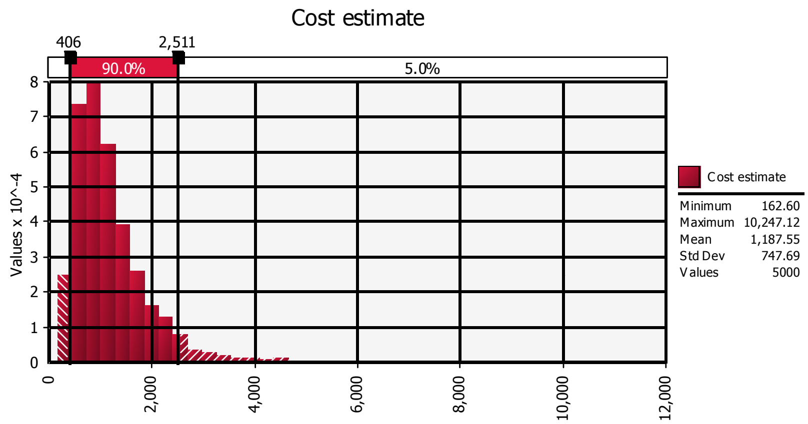

Figure 6.23. SR 99 tunnel project cost estimate (90% confidence interval)

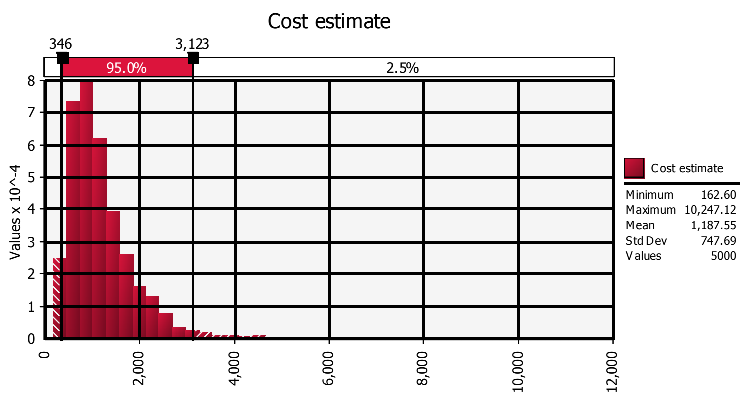

Figure 6.24. SR 99 tunnel project cost estimate (95% confidence interval)

6.9.2.3. Scenario 3 (10,000) Iterations

Scenarios 3, MC simulations using equation 6.1at the specified confidence intervals are depicted in Figures 6.21 to 6.24. The cost estimate ranges between a minimum of $491 million and a maximum of $2,106 million for the SR 99 tunnel project when factoring in uncertainty at 80% confidence interval. The cost estimate reaches a minimum of $349 million and a maximum of $3,055 million at 95% confidence interval with a standard deviation of $727.10 million.

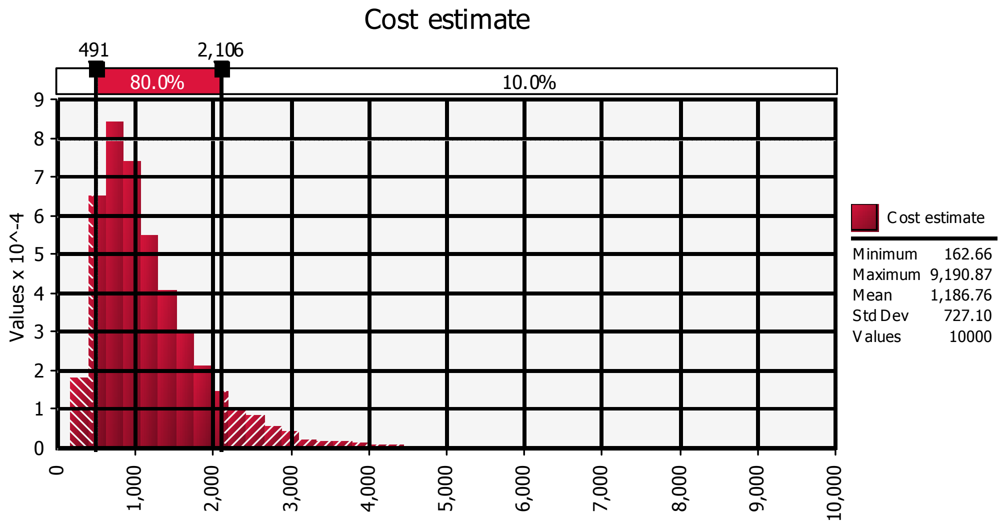

Figure 6.25. SR 99 tunnel project cost estimate (80% confidence interval)

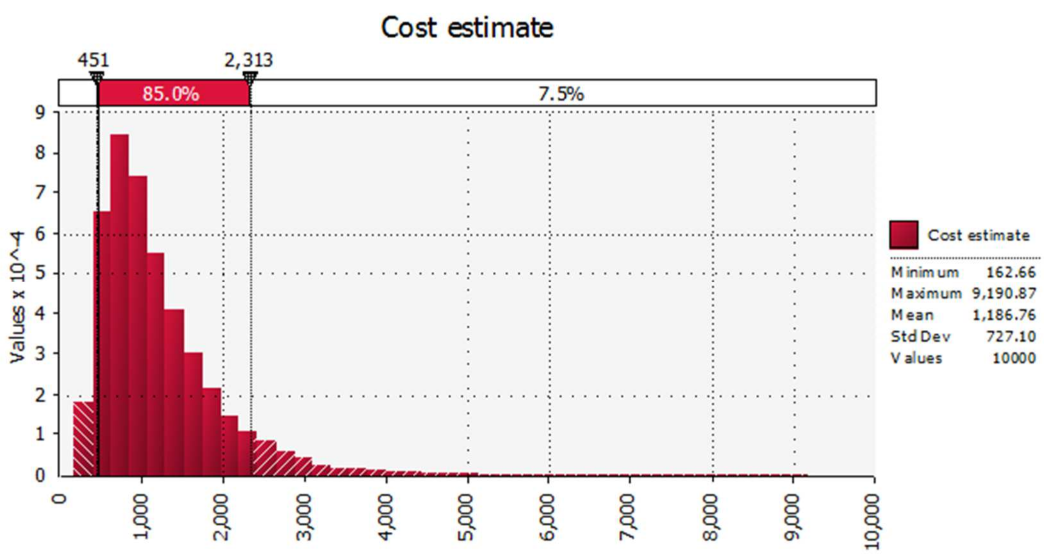

Figure 6.26. SR 99 tunnel project cost estimate (95% confidence interval)

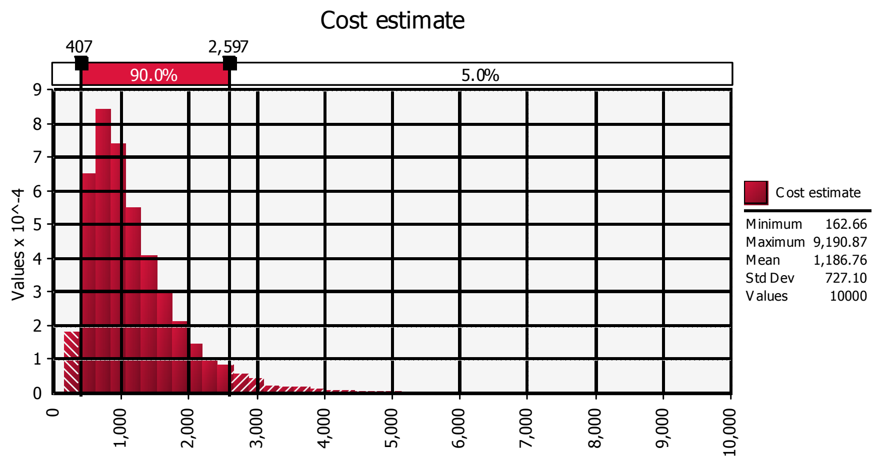

Figure 6.27. SR 99 tunnel project cost estimate (90% confidence interval)

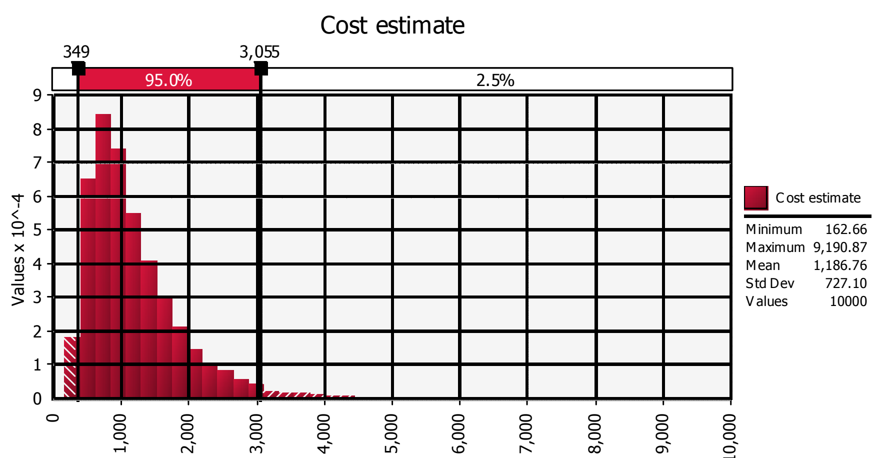

Figure 6.28. SR 99 tunnel project cost estimate (95% confidence interval)

Table 6.4. Summarizes the cost estimation results for the SR 99 Tunnel Project.

	80%		85%		90%		95%	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Scenario 1	502	1,990	457	2,239	408	2,496	342	3,154
Scenario 2	494	2,099	453	2,270	406	2,511	346	3,123
Scenario 3	491	2,106	451	2,313	407	2,597	349	3,055

All values in US dollars

CHAPTER 7. SUMMARY, CONCLUSIONS, AND FUTURE RESEARCH

7.1. Introduction

The research conducted in this dissertation emphasized the importance of employing parametric functions and quantification of associated risks to estimate transportation tunnel project costs. The research presented many highlights based on a comprehensive systematic literature review and numerous analyses, which can benefit personnel in the transportation tunneling construction sector.

7.2. Summary and Conclusions

Due to the increasing scrutiny of construction costs for infrastructure projects by the public and legislators, it is becoming increasing important to prepare accurate conceptual cost estimates at the feasibility stage to aid in making decisions to build. Cost underestimation is a fundamental problem facing transportation infrastructure projects when preparing conceptual cost estimates due to uncertainties and risks encountered and need to be included in the decision making process. Many of the models used to prepare cost estimates are based on deterministic assumptions without considering uncertainties (Rostami et al., 2013). Uncertainties, limited available information, and multiple unknown factors are the risks that impact tunnel project cost estimates and make their preparation process highly complex and challenging at the feasibility stage. It was found out that employing a stochastic method that quantifies associated risks improves the accuracy of cost estimates of large projects.

Estimating factors that were used in this study to develop stochastic cost functions were depth of overburden, tunnel length, and tunnel diameter. By studying different permutations, the research developed stochastic cost estimation functions and quantified associated risks as summarized.

A systematic literature review identified 40 estimating factors that contribute to cost underestimation in transportation tunnel projects published from 1988 to 2013 period. The cost factors were classified into 4 categories -internal factors, external factors, project specific factors, and other factors. The number of times a factor occurred in literature was used in ranking them with the most significant factors assigned highest number of occurrence. The top ranked factors were engineering and construction complexities, geological/ground conditions, poor estimating, economic and market conditions, environmental requirements, scope changes, size of project, technological innovation, political requirements and contract document conflicts. A total of three factors received one authors' opinion, which was ranked the lowest rank, 14. The lowest ranked factors were scope creep, inconsistent application of contingencies, and social issues.

A survey questionnaire gleaned from analysed literature was prepared, subjected to IRB approval, and posted to the respondents. The survey was conducted as per the approved IRB documents and sent out by mail to 39 organizations (22 DOTs, 3 MPOs, and 14 consultants) from April 1, 2014 to July 6, 2014. The response rate for the initial survey was 3 participants representing 8%. A second survey was performed by sending out emails to Dr. Rostami and Mr. Sepehrmanesh, some of the known researchers in tunnel costing. This second survey yielded 272 tunnel projects consisting of different sizes, applications, locations, and ground conditions from North America. From the original dataset, a new database covering transportation tunnel projects was developed and resulted in a sub database with 79 tunnel projects. The study adjusted tunnel costs for the new database tunnel costs using the construction cost index to obtain the tunnel project's year of construction costs to account for time and location to adjust them to the base year (March, 2014). The CCI is commonly used by cost estimators, investment planners, and financial institutions to estimate construction costs, prepare budgets during the planning phase, and undertake cost control during the construction phase (Touran and Lopez, 2006; Ashuri and Lu, 2010; Xu and Moon, 2013). The study performed exploratory data analysis and cost curve fitting on the influential cost parameters of the data acquired to discover any correlations among the tunnel parameters. It involved fitting curves to total tunnel cost against depth of overburden, length of tunnel, and diameter of tunnel.

Four mode of transportation functions were developed using step wise regression analysis for predicting tunnel cost estimates. The functions were developed based on the method of excavation and type of geology by analysing tunnel parameters that impact tunnel cost estimate. In addition, hypotheses testing were performed on the independent variables and the dependent variable for the different conditions. Analyses of impact on tunnel cost estimate were performed using the developed functions to estimate tunnel cost and plotting estimated tunnel cost against actual cost graphs to reveal the accuracy of the functions developed and revealed interesting findings.

The case studies discussed in this study show the applicability of parametric cost estimation functions in transportation tunneling projects. The parametric functions employed in the case studies analyses were based on the method used to bore the highway tunnel project. For the two case studies selected, there was no particular function developed for the highway mode of transportation for the TBM method, hence the general functions were used to analyze them. For the two functions were selected, one was associated with mode of transportation and the other type of geology to quantify associated risks. Monte Carlo simulation was used to determine associated quantification of risk. In this research, risk quantification involved defining the known and uncertain inputs, outputs, and the formulas that contain the logic for calculating outputs from inputs. For the known and uncertain inputs, normal distributions with known mean and standard deviation were used, while the estimate cost output followed a beta distribution. Associated risk quantification was determined for the Miami tunnel project and SR 99 tunnel project using the selected functions developed for this type of application. The two case studies were for the highway mode of transportation. An important observation show that the proposed stochastic function performed better compared to the deterministic function. The findings of this study solve the problem facing many transportation personnel in terms of the need for quantifying associated risks to support decision makers when making decisions to build. The results of the case studies illustrate the need to use Monte Carlo simulation technique to simulate tunnel costs and provide the associated risks of the estimated tunnel costs.

7.3. Future Work

The findings of this research provide useful information for future research related to cost estimation of transportation tunnel projects. As for the issues associated with risk factors, the following directions could be a viable extension to the current study:

- Conduct a national survey and establish risk factor weights for developing a metric that could be employed to enhance cost estimation by engineers and estimators to make reasonable conceptual cost estimate predictions for transportation tunnel projects.
- Develop an electronic database for transportation tunnel projects to help develop predictability functions, as well as identifying all the variables impacting tunnel cost. As such more ways are needed for a multi-agency involvement to collect quantitative and qualitative data.
- Develop a framework for tunnel cost estimation and risk analysis.
- Develop parametric functions that incorporate risk/uncertainty using nonlinear regression and other techniques to enhance the cost estimates.

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APPENDIX A. IRB LETTER

NDSU NORTH DAKOTA STATE UNIVERSITY

February 3, 2014

Dr. Eric Asa
Dept of Construction Management & Engineering

Re: Your submission to the IRB: "Parametric Cost Estimating and Risk Analysis of Tunneling Projects"

Research Team: Mr. Joseph Membah

Thank you for your inquiry regarding your project. At this time, the IRB office has determined that the above-referenced protocol does not require Institutional Review Board approval or certification of exempt status because it does not fit the regulatory definition of 'research involving human subjects'.

Dept. of Health & Human Services regulations governing human subjects research (45CFR46, *Protection of Human Subjects*), defines 'research' as "... a systematic investigation, research development, testing and evaluation, designed to contribute to generalizable knowledge." These regulations also define a 'human subject' as "... a living individual about whom an investigator conducting research obtains (1) data through intervention or interaction with the individual, or (2) identifiable private information."

It was determined that your project does not require IRB approval (or certification of exempt status) because the survey seeks to obtain information about organizational policies and practices rather than individuals. The board makes this determination conditional on the survey instrument provided on 1/29/2014.

We appreciate your intention to abide by NDSU IRB policies and procedures, and thank you for your patience as the board has reviewed your study. Best wishes for a successful project!

Sincerely,

Kristy Shirley

Kristy Shirley, CIP; Research Compliance Administrator

INSTITUTIONAL REVIEW BOARD
NDSU Dept 4000 | PO Box 6050 | Fargo ND 58108-6050 | 701.231.8995 | Fax 701.231.8098 | ndsu.edu/irb

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APPENDIX B. SURVEY QUESTIONNAIRE FOR COST ESTIMATION

Research Intent: Cost Estimation for Transportation Tunneling Projects

Dear Participant,

This research is conducted by Joseph Membah, under the direction of Dr. Eric Asa; an Associate Professor in the Department of Construction Management and Engineering at the North Dakota State University, Fargo, North Dakota. The data collected will be used to develop a parametric cost estimation model for tunnel projects.

Estimating the construction cost of transportation tunneling projects during the feasibility stage is complex and challenging to state/federal agencies and Metropolitan Planning Organizations. Consequently, estimating the construction cost is a major problem since project costs are significantly underestimated and cost overruns have been the bane of the tunnel construction industry. At feasibility stage, limited information is available concerning the project and it is difficult to compare different alternatives.

The purpose of this research survey is to collect data on factors driving cost estimation of tunnels, risk, and other information related to highway tunneling projects. This survey is intended to collect data from consultants, contractors, owners, project managers, and other professionals from both private and public sectors in the transportation industry. The data will be used to develop a parametric cost estimation function for tunnel projects. The cost estimation function developed could benefit state/federal agencies, Metropolitan Planning Organizations, and consultants engaged in estimating the cost of transportation tunneling projects.

You are being kindly requested to participate in this research study. It would take 20-25 minutes to complete the entire survey. The survey is based on filling out and making check marks in associated boxes. Your participation is voluntary, and you may change your mind or quit participating at any time; with no penalty to you. However, your assistance would be highly appreciated in making this a meaningful study. We encourage you to take your time and complete the enclosed survey and return it by fax to 701.231.7431 or email to Eric.Asa@ndsu.edu or Joseph.Membah@ndsu.edu.

Thank you for taking part in this research. If you have questions about your rights as a participant, or to report a problem, contact NDSU Institutional Review Board (IRB) office at ndsu.irb@ndsu.edu, or 701.231.8908 or toll free 1.855.800.6717. If you wish to receive a copy of the research or have questions about this research or your participation in this study, please email Dr. Eric Asa, at Eric.Asa@ndsu.edu or Joseph Membah at Joseph.Membah@ndsu.edu .

Your participation is highly appreciated.

Sincerely,

Eric Asa, Ph.D.
Associate Professor and Director, Computational and Sustainable Infrastructure Laboratory (CSI Lab).

SURVEY QUESTIONNAIRE FOR COST ESTIMATION

PART I: GENERAL ORGANIZATION INFORMATION

The questions refer to estimates prepared at the feasibility phase for a transportation tunnel project.

1. What organization do you work for?

   ☐State Department Agency (DOT) ☐ Public Agency (MPO) ☐Design Firm

   ☐Contractor/Subcontractor ☐A/E Consultant ☐other (state) Click here to enter text.

2. How many years of experience do you have in estimating tunnel projects? ☐

3. Does your organization have a formal training program for new and old employees in estimating? ☐ Yes ☐ No

   If yes would you describe it?

4. Are there standard guidelines to follow when preparing cost estimates? ☐Yes ☐No

   If yes would you describe them?

PART II: COST ESTIMATION

5. What cost estimation methods best describes the process used by your organization to compute the initial cost of tunneling projects? Select all that apply.

   ☐ Unit per feet ☐ Unit per square feet ☐ Capacity-factored

   ☐ Judgment ☐ Analogy ☐ Parametric

   Others (specify) …………………………………………………

6. Name the tools your organization uses to calculate tunnel project cost? (Select all that apply)

   ☐ Software ☐ Manual Calculation ☐ Both methods

   Other (specify) …………………………………

7. Type of cost estimating software (specify)………………………………………………

8. Type of risk analysis software (specify)………………………………………………

9. What equations does your organization commonly uses to calculate the initial cost of a tunnel project?

10. Does your organization follow specific practices and procedures to select a cost estimation method? ☐Yes ☐No other please specify ……………………………………….

    If yes, please explain further,

11. How satisfied is your organization with the current method used to calculate initial tunnel cost?

12. What are the challenges experienced when using the current method to calculate initial tunnel cost?

13. What are the possible reasons for differences in initial and final costs of tunnel projects?

14. Explain the cost estimation and decision-making processes followed to calculate initial tunnel costs?

Use the information presented in Figure B1 and Table B1 to complete the geology section in Question 15.

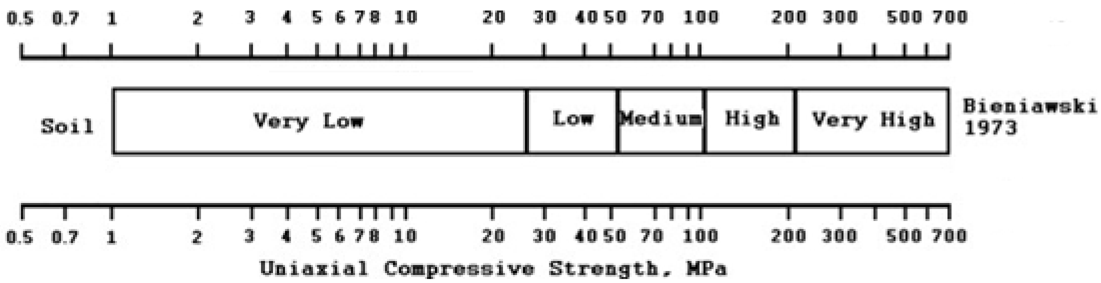

Figure B1. Classifications based on material strength.

Table B1. Ground classification in relation to tunnel design.

Classification	Uniaxial compressive strength (MPa)	Ground types
Soft ground (Soil)		(a) Recent alluvium and glacial drift deposits including water-bearing sands, gravels, silts, and clays, and boulder clay. (b) Eocene, Cretaceous and Jurassic stiff fissured clays
Very low strength rock (Very Low)	Up to 25	Low strength rocks including shales, Cretaceous Chalk, Triassic (Keuper) Marl and Jurassic rock formations. Material crumbles under firm blow with a sharp end of a geological pick and can be peeled off with a knife.
Low strength rock (Low)	25 - 50	Low strength rocks including shales, Cretaceous Chalk, Triassic (Keuper) Marl and Jurassic rock formations. Material can be scraped and peeled with a knife.
Medium strength rock (Medium)	50-100	Many Triassic and Permian rock formations, sandstones and medium strength Carboniferous Coal Measures. Specimen can be broken with the hammer end of a geological pick with a single firm blow.
High strength rock (High)	100 - 200	The hard Carboniferous and older rocks, limestone and harder rocks. Hand-held specimen breaks with hammer end of pick under more than one blow.
Very high strength rock (Very High)	Above 200	The hard Carboniferous and older rocks, limestone and harder rocks. Specimen requires many blows with geological pick to break through intact material.

15. In Table B2 enter end use (rail or highway), year construction started, year completed, tunnel burial depth, outside diameter, inner diameter, type of tunnel (indicate with X in the appropriate box), initial, and final costs of the transportation tunnel projects involved.

For the geology sections indicate with an X in the appropriate box of the class of the rock material (with reference to the information presented in Figure B1 and Table B1 above).

Table B2 First Tunnel Project Details:

Name of tunnel project					
Location					
End use		Date Started		Date Completed	
Depth of tunnel burial (ft)		Outside diameter (ft)		Inner diameter (ft)	
Type of tunnel	☐Cut & cover	☐Drill and blast	☐Tunnel boring method (TBM)	☐New Austrian Tunneling Method (NATM)	
Length of tunnel		Tunnel location	☐Urban area	☐Other areas	
Geology	☐ Soil	☐Very low	☐Low	☐Medium	☐High
	☐Very high	Indicate uniaxial compressive strength			
Initial tunnel cost estimate		Final tunneling cost			
Comments and problems if any					

Second Project Details

Name of tunnel project					
Location					
End use		Date Started		Date Completed	
Tunnel burial depth (ft)		Outside diameter (ft)		Inner diameter (ft)	
Type of tunnel	☐Cut & cover	☐Drill and blast	☐Tunnel boring method (TBM)	☐New Austrian Tunneling Method (NATM)	
Length of tunnel		Tunnel location	☐Urban area	☐Other areas	
Geology	☐ Soil	☐Very low	☐Low	☐Medium	☐High
	☐Very high	Indicate uniaxial compressive strength			
Initial tunnel cost estimate		Final tunneling cost			
Comments and problems					

Third Project Details

Name of tunnel project					
Location					
End use		Date Started		Date Completed	
Depth of tunnel burial (ft)		Outside diameter (ft)		Inner diameter (ft)	
Type of tunnel	☐Cut & cover	☐Drill and blast	☐Tunnel boring method (TBM)	☐New Austrian Tunneling Method (NATM)	
Length of tunnel		Tunnel location	☐Urban area	☐Other areas	
Geology	☐ Soil	☐Very low	☐Low	☐Medium	☐High
	☐Very high	Indicate uniaxial compressive strength			
Initial tunnel cost estimate		Final tunneling cost			
Comments and problems if any					

Please add more tables based on the total number of projects being reported by copying and pasting Table B2 as needed.

PART III: FACTORS DRIVING COST UNDERESTIMATION IN TRANSPORTATION TUNNELS

16. Please indicate the significance of each tunnel cost driving factor by placing an X in the appropriate boxes. Add any remarks relating to each cost factor on the last (Remarks) column.

VL = very low L = low M = moderate H = high
VH = very high NS = not significant

Hypothesized cost factors	VL	L	M	H	VH	NS	Remarks
Internal Factors							
• Bias	☐	☐	☐	☐	☐	☐	
• Delivery/procurement approach	☐	☐	☐	☐	☐	☐	
• Project schedule changes	☐	☐	☐	☐	☐	☐	
• Engineering complexities	☐	☐	☐	☐	☐	☐	
• Construction complexities	☐	☐	☐	☐	☐	☐	
• Scope creep	☐	☐	☐	☐	☐	☐	
• Poor estimating (cost estimation)	☐	☐	☐	☐	☐	☐	
• Underestimating contingencies	☐	☐	☐	☐	☐	☐	
• Faulty project execution	☐	☐	☐	☐	☐	☐	
• Contract document conflicts	☐	☐	☐	☐	☐	☐	
External Factors							
• Local government concerns and requirements	☐	☐	☐	☐	☐	☐	
• Effects of inflation	☐	☐	☐	☐	☐	☐	
• Project scope	☐	☐	☐	☐	☐	☐	
• Scope creep	☐	☐	☐	☐	☐	☐	
• Economic and market conditions	☐	☐	☐	☐	☐	☐	
• Unforeseen events	☐	☐	☐	☐	☐	☐	
• Unforeseen conditions	☐	☐	☐	☐	☐	☐	
Project Specific Factors							
• Duration of project	☐	☐	☐	☐	☐	☐	
• Size of project	☐	☐	☐	☐	☐	☐	
• Geological/ground conditions	☐	☐	☐	☐	☐	☐	

	VL	L	M	H	VH	NS	
• Support requirements	☐	☐	☐	☐	☐	☐	
• Site investigation	☐	☐	☐	☐	☐	☐	
• Excavation methods	☐	☐	☐	☐	☐	☐	
• Safety	☐	☐	☐	☐	☐	☐	
• Changes on project specifications and design	☐	☐	☐	☐	☐	☐	
• Tunnel diameter	☐	☐	☐	☐	☐	☐	
• Tunnel length	☐	☐	☐	☐	☐	☐	
• Depth of overburden	☐	☐	☐	☐	☐	☐	
Other Factors							
• Type of project ownership	☐	☐	☐	☐	☐	☐	
• Geographical location	☐	☐	☐	☐	☐	☐	
• Water problems	☐	☐	☐	☐	☐	☐	
• Social issues	☐	☐	☐	☐	☐	☐	
• Technological innovations	☐	☐	☐	☐	☐	☐	
• Government standards and regulations	☐	☐	☐	☐	☐	☐	
• Local government pressures	☐	☐	☐	☐	☐	☐	
• Lack of organizational capacity	☐	☐	☐	☐	☐	☐	
• Inexperienced personnel	☐	☐	☐	☐	☐	☐	

If there are reports you might want to share with us, please feel free to send them.

Please send copies and any other reports documenting cost estimation of transportation tunneling projects to:

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WE APPRECIATE YOUR RESPONSE – THANK YOU